Effects of Pumping Municipal Wells at Junction City, Kansas, on Streamflow in the Republican River, Northeast Kansas, 1992–94

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per second (acre-ft/s)	1,233	cubic meter per second
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day[1] (ft/d)	0.3048	meter per day
foot per day[1] (ft/d)	3.5278×10^{-4}	centimeter per second
foot per second (ft/s)	0.3048	meter per second
foot squared per day[2] (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

[1]See definition for hydraulic conductivity.

[2]See definition for transmissivity.

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the equations:

$$°C = 5/9\ (°F - 32),$$
$$°F = 9/5\ (°C) + 32.$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

DEFINITION OF TERMS

Aquifer. A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Evapotranspiration. Water withdrawn from a land area by evaporation from water surfaces and moist soil, and by plant transpiration.

Gaging station. A particular site on a stream, canal, lake, or reservoir where systematic observations of gage height or streamflow are obtained.

Hydraulic conductivity. The volume of water at the existing kinematic viscosity that will move in unit time under a unit **hydraulic gradient** through a unit area measured at right angles to the direction of flow. The standard unit for **hydraulic conductivity** is cubic foot per day per square foot [$(ft^3/d)/ft^2$)]. This mathematical expression reduces to foot per day (ft/d).

Hydraulic gradient. Change in total **hydraulic head** per unit of distance in a given direction.

Hydraulic head. Height above a standard datum of the surface of a water column that can be supported by the static pressure at a given point.

Potentiometric surface. A surface that represents the level to which water will rise in a tightly cased well. More than one **potentiometric surface** may be required to describe the distribution of **hydraulic head** if **hydraulic head** varies appreciably with depth in the **aquifer**.

Recharge. The processes involved in the addition of water to the zone of saturation.

Saturated thickness. The thickness of the saturated zone in an **aquifer**.

Specific capacity. The volume of water yielded from a well per unit of drawdown in the well.

Specific yield. The ratio of the volume of water that saturated rock or sediment will yield by gravity to the volume of the rock or sediment.

Steady state. Condition under which the magnitude and direction of ground-water flow velocities are constant with time, and water inflow and outflow from the **aquifer** are constant.

Transient. Condition under which the magnitude and direction of ground-water flow velocities vary with time, and water inflow and outflow from the **aquifer** are not constant.

Transmissivity. The volume of water at the existing kinematic viscosity that will move in unit time under a unit **hydraulic gradient** through a unit width of the **aquifer**. The standard unit for **transmissivity** is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)ft^2$)/ft]. This mathematical expression reduces to foot squared per day (ft^2/d).

Effects of Pumping Municipal Wells at Junction City, Kansas, on Streamflow in the Republican River, Northeast Kansas, 1992–94

By Nathan C. Myers, Xiaodong Jian, *and* Gerald D. Hargadine

Abstract

A digital ground-water flow model was developed to simulate steady-state and transient effects of municipal well pumping from an alluvial aquifer on streamflow in the Republican River near Junction City, Kansas. Seepage survey results indicated that streamflow loss in the vicinity of the municipal well field ranged from 1 to 5 ft^3/s (cubic feet per second). Simulations of May 1993 conditions indicate that well pumping decreased simulated streamflow by an average of 3.03 ft^3/s for the month, of which 2.45 ft^3/s was induced infiltration from the stream and 0.58 ft^3/s was intercepted base flow. Of the total well pumpage for May 1993 (265 acre-feet), about 57 percent was from induced infiltration from the river, about 13 percent was from intercepted base flow, and about 30 percent was from decreased aquifer storage, outflow from the aquifer, evapotranspiration, and increased recharge and inflow to the aquifer. Simulations of November 1994 conditions indicate that well pumping decreased simulated streamflow by an average of 3.15 ft^3/s for the month, of which 1.0 ft^3/s was contributed from the stream and 2.15 ft^3/s was contributed from intercepted base flow. Of the total well pumpage for November 1994 (264 acre-feet), about 22 percent was from induced infiltration from the river, about 48 percent was from intercepted base flow, and about 30 percent was from decreased aquifer storage, outflow from the aquifer, evapotranspiration, and increased recharge and inflow to the aquifer. Steady-state simulations of hypothetical conditions were conducted to develop graphs that show the relations among ground-water levels in the well field, pumping rate, and streamflow.

INTRODUCTION

Background

Alluvial aquifers of the Kansas and Republican Rivers provide an important source of water to industry and agriculture in northeast Kansas and are a sole source of water to some public suppliers. During periods of low streamflow, water releases from Milford Reservoir and other reservoirs on Kansas River tributaries have been used to maintain streamflow at desirable rates. Water-release rates from the reservoirs have been determined on the basis of the needs of river-water users and State of Kansas minimum desirable streamflow requirements [Kansas Statutes Annotated (K.S.A.) 82a.703]. However, ground-water withdrawals from the alluvial aquifer, which may induce significant recharge of river water into the aquifer, generally are not considered when making reservoir releases. Consideration of ground-water withdrawals is especially important during periods of low streamflow when ground-water withdrawals may substantially decrease streamflow and the amount of water available to river-water users.

Beginning in 1992, separate 3-year studies to determine the effects of pumping municipal wells in the alluvial aquifers at Junction City and Manhattan, Kansas, on streamflows in the Republican, Big Blue, and Kansas Rivers were conducted by the U.S. Geological Survey (USGS) in cooperation with the Kansas Water Office. A seperate report is planned for the Big Blue and Kansas River study. The amount of river water that infiltrates into the aquifers to satisfy pumping demands needed to be quantified so that the effect of pumping during low streamflow conditions could be assessed. This study was particularly relevant to the Kansas River Water Assurance District, whose members are municipal and industrial entities that hold water rights along the Kansas River and include Junction City and Manhattan. This study was also done to develop a better understanding of the effects of municipal well-field pumping in alluvial-aquifer settings on streamflow.

Purpose and Scope

This report presents the results of the study of the effects of known and hypothetical municipal well pumping at Junction City, Kansas, on streamflow in the Republican River. This report presents data for the Junction City study area (fig. 1), including geology, hydrology, stream-aquifer hydraulic interaction, and water use (1960–94), and the results of ground-water flow model simulations of the effects of known and hypothetical municipal ground-water pumping on streamflow in the Republican River.

Description of Study Area

Regionally, the study area is located in the Flint Hills Upland physiographic division (fig. 1) (Schoewe, 1949), which is a prominent upland area characterized by rolling topography and deep stream valleys with steep valley walls. Most of the study area lies within the low-relief flood plains of the Republican, Smoky Hill, and Kansas River Valleys (fig. 2). The study area includes the reaches of the Republican, Smoky Hill, and Kansas Rivers as follows: the Republican River from Milford Dam to its confluence with the Smoky Hill River; the Smoky Hill River from a point on the river near the southern edge of Junction City to its confluence with the Republican River; and the Kansas River from the confluence of the Republican and Smoky Hill Rivers to about 3 river mi downstream from the USGS gaging station at Fort Riley (Kansas River at Fort Riley).

Milford Dam, completed in August 1967, was built on the Republican River for flood-control, water-supply, streamflow regulation, recreation, and fish and wildlife management purposes. The dam is located about 4.5 river mi upstream from Junction City and about 7.7 river mi upstream from the confluence of the Republican and Smoky Hill Rivers.

The Junction City municipal well field is located on the southwest bank of the Republican River about 4.5 river mi downstream from Milford Dam. Currently (1995), there are 10 municipal supply wells in operation at the well field. All of the wells are located within 1,000 ft of the riverbank, and six are located within 500 ft of the riverbank.

Approach

Information pertaining to well locations, well construction, geology, and hydrology was obtained from the Junction City Engineer's Office, the Kansas Water Office (KWO), the Kansas Department of Health and Environment (KDHE), Fort Riley's Planning and Restoration Division, the U.S. Army Corps of Engineers (ACE), the USGS, well owners, and published reports. Water-use information was obtained from Junction City, the Kansas Department of Agriculture's Division of Water Resources (DWR), and Fort Riley.

Bedrock-surface altitudes were obtained from several sources, including published lithologic logs, boreholes drilled during this study, ACE Milford Dam construction records, Junction City municipal well construction records, Fort Riley monitoring and supply well records, and WWWC-5 forms (well drillers' logs) on file with KDHE. Bedrock-surface altitude was defined in this study as the altitude of the geologic contact between alluvium and underlying rock, usually shale or limestone. These altitudes were used to construct a bedrock-surface paleotopography map and to define aquifer thickness for the ground-water flow model.

Observation wells located in and near the Junction City municipal well field (fig. 2) were installed by the USGS during September and November 1992 and January 1993. Boreholes for observation wells USGS–1 through USGS–3, USGS–5 through USGS–9, USGS–12, and USGS–13 were drilled using 4 1/4-in. inside-diameter, hollow-stem augers. All equipment and materials were cleaned with a high-pressure jet of potable water prior to installation of each well. A steel plate, placed in the auger bit, prevented sediment from clogging the inside of the auger flights while drilling. At the desired depth, the auger flights were filled with potable water to compensate for hydrostatic pressure outside the auger flights, then the pipe for the

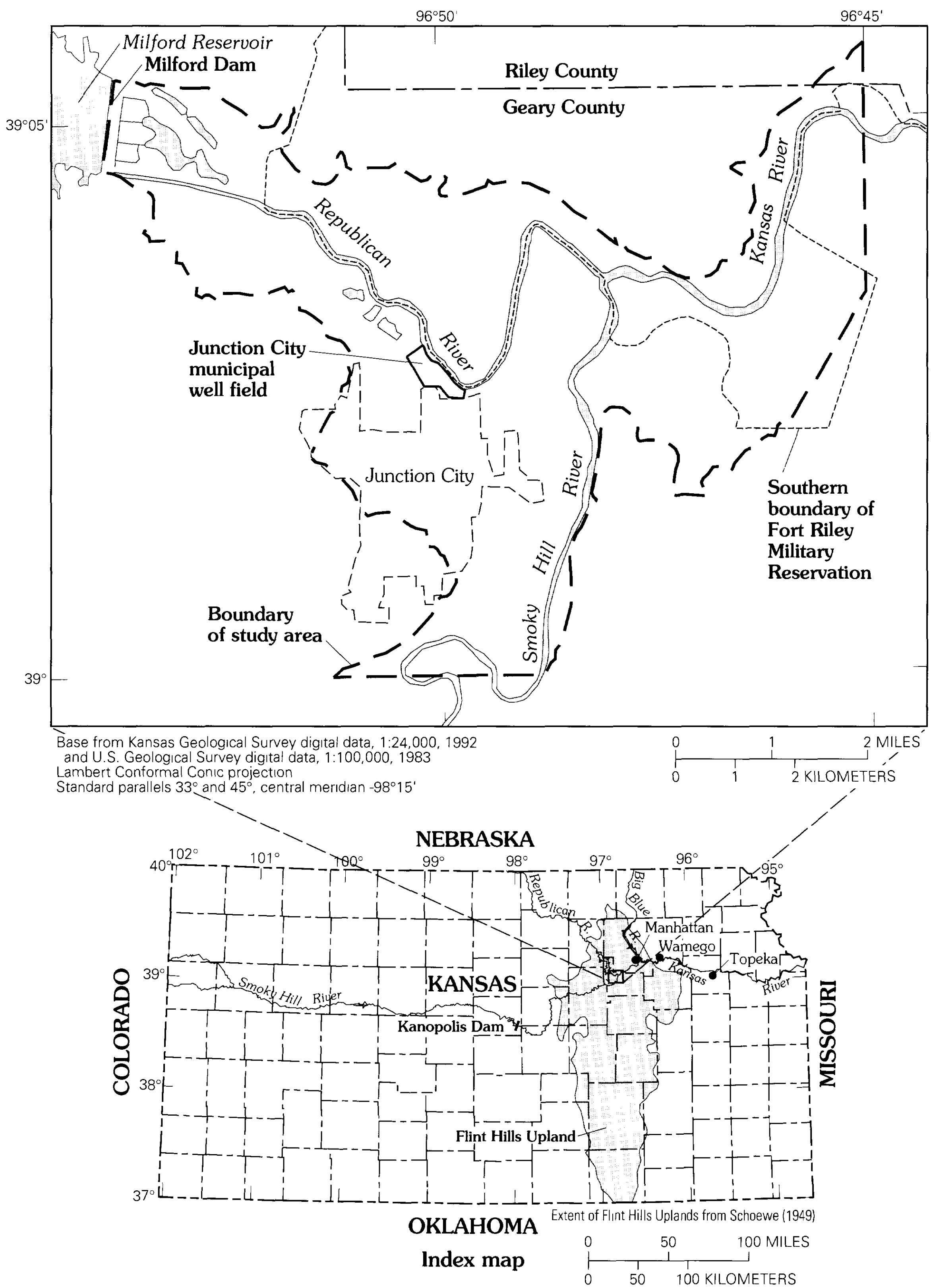


Figure 1. Location of study area.

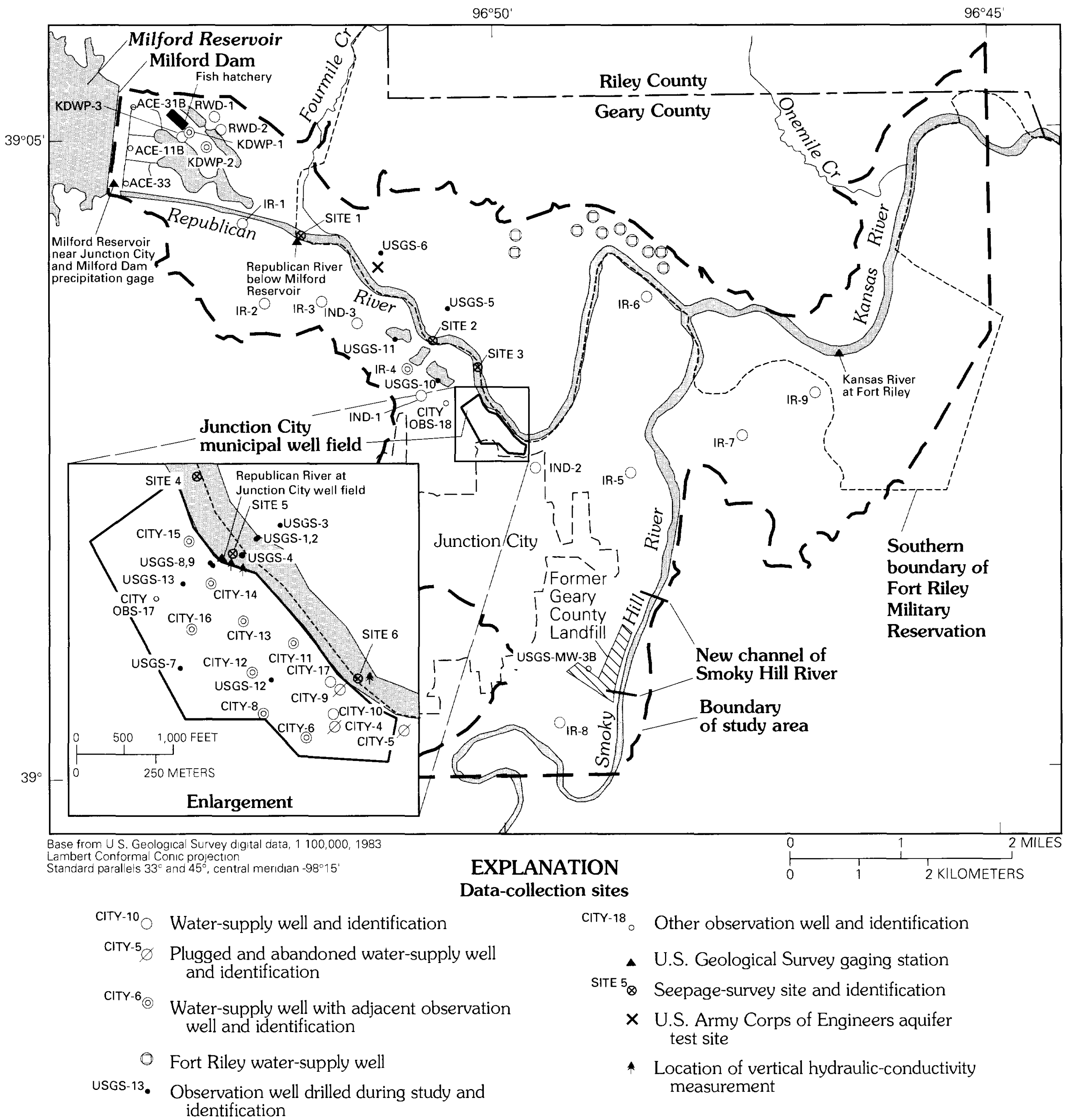


Figure 2. Location of study area, streams, data-collection sites, and Junction City municipal well field.

observation well was lowered inside the auger flights and was used to knock out the steel plate in the auger bit. Observation wells were 2-in. inside-diameter, polyvinyl-chloride (PVC) pipe that had flush-threaded joints (no glue or solvent was used), a 5-ft PVC screen with 0.01-in. slots, and a capped bottom. The screen and pipe were centered in the hole as the auger flights were removed. Natural sand packing resulted from the caving of sand as the auger flights were removed. About 2 ft of bentonite chips were placed on the top of the natural sand pack and allowed to hydrate for 1 to 2 hours, then a high-solids bentonite grout was added to the annular space using a tremie pipe to within 18 in. of land surface. Finally, bentonite chips were added from 18 in. to land surface. The wells were developed using filtered compressed air. The air provided a surging action and was continued until the turbidity cleared. A locking steel casing was set over the PVC well casing.

The borehole for observation well USGS–4 was hand augered in streambed sediment near the stream. At the desired depth, the observation well, consisting of 1 1/2-in. inside-diameter well point and galvanized steel pipe, was lowered into the borehole. Natural sand was allowed to collapse around the well screen and pipe to the surface.

Observation wells USGS–10 and USGS–11 were driven into the aquifer at the water's edge of sand pits using a sledge hammer. The observation wells consisted of 1 1/2-in. inside-diameter well point and galvanized steel pipe.

Observation wells USGS–1 through USGS–3, USGS–5 through USGS–7, USGS–12, and USGS–13 were equipped with digital punch-tape water-level recorders. Water levels in these wells were recorded at hourly intervals. Observation wells USGS–8 and USGS–9 initially were equipped with shaft encoders and later with submersible pressure transducers. These instruments were connected to a data logger-transmitter, which collected water-level data at 15-minute intervals.

A network of observation wells (fig. 2), in addition to the USGS wells and consisting of existing city observation wells, irrigation wells, ACE observation wells, and a landfill observation well in the study area, was established for the purpose of collecting water-level data in and around the well field. These wells were variable in depth but generally were screened across the water table and were measured about monthly during this study.

Geologic information was recorded while drilling. Gamma-ray logs were obtained from USGS boreholes drilled to bedrock. Top-of-casing altitudes were determined by level survey (table 1). Water levels were measured to the nearest 0.01 ft using a steel tape. Water-level altitudes were used to construct potentiometric-surface maps for selected dates to show directions of ground-water flow and the interaction of ground water and surface water. Streamflow measurements for seepage surveys were conducted using standard USGS methods (Rantz and others, 1982).

A stage-only gaging station was established at the edge of the well field adjacent to observation wells USGS–8 and USGS–9. Stream stage was measured initially with a submersible pressure transducer fixed in place inside the end of an orifice pipe anchored in the streambed. After sustaining freeze damage, the submersible transducer was replaced with a gas-purge system and a nonsubmersible transducer. Steel fence posts, driven at intervals down the streambank, served as external reference points for measuring stream stage. The pressure transducer was connected to a data logger-transmitter, which collected stream-stage data at 15-minute intervals.

Table 1. Top-of-casing altitudes for observation wells used in this study

Well name (fig. 2)	Top-of-casing altitude (feet)	Well name (fig. 2)	Top-of-casing altitude (feet)
USGS–1	1,066.81	CITY–11	1,071.18
USGS–2	1,066.98	CITY–12	1,069.31
USGS–3	1,074.39	CITY–13	1,067.98
USGS–4	1,056.62	CITY–14	1,069.93
USGS–5	1,072.90	CITY–15	1,071.87
USGS–6	1,079.13	CITY–16	1,072.83
USGS–7	1,084.85	CITYOBS–17	1,072.04
USGS–8	1,071.51	CITYOBS–18	1,086.09
USGS–9	1,071.69	IR-4	1,074.01
USGS–10	1,058.08	KDWP–1	1,077.30
USGS–11	1,057.35	KDWP–2	1,077.88
USGS–12	1,069.41	ACE–11B	1,087.80
USGS–13	1,070.98	ACE–31B	1,089.30
CITY–6	1,084.99	ACE–33	1,088.90
CITY–8	1,083.21	USGS–MW–3B (former Geary County Landfill)	1,073.12

The vertical hydraulic conductivity of the Republican River streambed near the well field was determined by using a potentiomanometer and a seepage meter. Design and use of these instruments are described by Lee (1977) and Winter (1988). The potentiomanometer was used to measure the hydraulic-head difference between the ground water and surface water, and the seepage meter was used to measure the volume of water flowing between the aquifer and the river. Darcy's law, expressed by equation 1 below, was used to calculate the vertical hydraulic conductivity of the streambed at three locations near the well field (fig. 2).

$$K = \frac{Q}{A\left(\frac{dh}{dl}\right)}, \qquad (1)$$

where K is vertical hydraulic conductivity, in feet per second;

Q is the volume of water flowing between the aquifer and the river measured with the seepage meter, in cubic feet per second;

A is the area over which Q was measured, in square feet; and

$\frac{dh}{dl}$ is the hydraulic-head difference measured with the potentiomanometer, dimensionless.

Previous Studies

General studies of geology and (or) hydrology near the study area include "The Geology of Riley and Geary Counties, Kansas" by Jewett (1941), "Ground-Water Conditions in the Smoky Hill Valley in Saline, Dickinson, and Geary Counties, Kansas" by Latta (1949), and "Ground Water in the Kansas River Valley, Junction City to Kansas City, Kansas" by Fader (1974). Myers and Bigsby (1989) described the hydrogeology and ground-water-quality conditions at the former Geary County Landfill, near Junction City.

No previous reports of ground- and surface-water interaction studies or ground-water flow model development for the study area have been published. A ground- and surface-water interaction study using a finite-element, ground-water flow model (Wolf and Helgesen, 1993) was done for a reach of the Kansas River Valley between Wamego and Topeka, Kansas, about 40 river mi downstream of the study area.

Acknowledgments

The authors appreciate the cooperation of Junction City and Fort Riley officials, who provided access to drilling sites and data for the study, and to landowners and the ACE, who gave permission for water-level data to be collected from observation wells.

GEOLOGY AND HYDROLOGY

Geology

The study area is located on alluvial and terrace deposits of the Republican, Smoky Hill, and Kansas Rivers (fig. 3). On the basis of geologic information from wells drilled during this study and data published by Latta (1949), the alluvium generally consists of as much as an 80-ft thick sequence of gravel, coarse-to-fine sand, and silt, with interbedded clay layers (table 11 at end of this report). The coarser sediments were generally found near the bottom of the alluvial deposits. The alluvial deposits occupy stream channels eroded into the bedrock surface (fig. 4) during Pleistocene and Holocene time (Frye and Leonard, 1952). Most of the alluvium probably was deposited in the bedrock stream channels during periods of glacial retreat (Frye and Leonard, 1952). Alluvial deposits are defined by Fader (1974, p. 4) as occurring "...from the river to the first distinguishable escarpment toward the valley wall on either or both sides of the river... ."

Newman and Buck Creek terrace deposits (fig. 3) consist of fining-upward sequences of gravel, sand, silt, and clay (Fader, 1974). Newman terrace deposits occur from the first escarpment to the next escarpment (progressing toward the valley wall), and Buck Creek terrace deposits, where present, generally occur adjacent to the valley wall (Fader, 1974).

Alluvial and terrace deposits are underlain by shale and limestone of Permian age. Depending upon the depth to which the bedrock was eroded in the stream channels (fig. 4), bedrock could be, from oldest to youngest, the Beattie Limestone to the Florence Member of the Barnestone Limestone (Jewett, 1941). The oldest bedrock encountered in boreholes drilled by the ACE near the axis of Milford Dam was the Schroyer Member of the Wreford Limestone. Because bedrock dips northwest in the study area and because bedrock-surface altitude decreases in the downstream direction (fig. 4), bedrock in the stream channel is progressively older downstream in the study area.

Surface Water

The Republican River, which drains areas of Kansas, Nebraska, and Colorado, and the Smoky Hill River, which drains areas of Kansas and Colorado, join at Junction City to form the Kansas River. Flow in

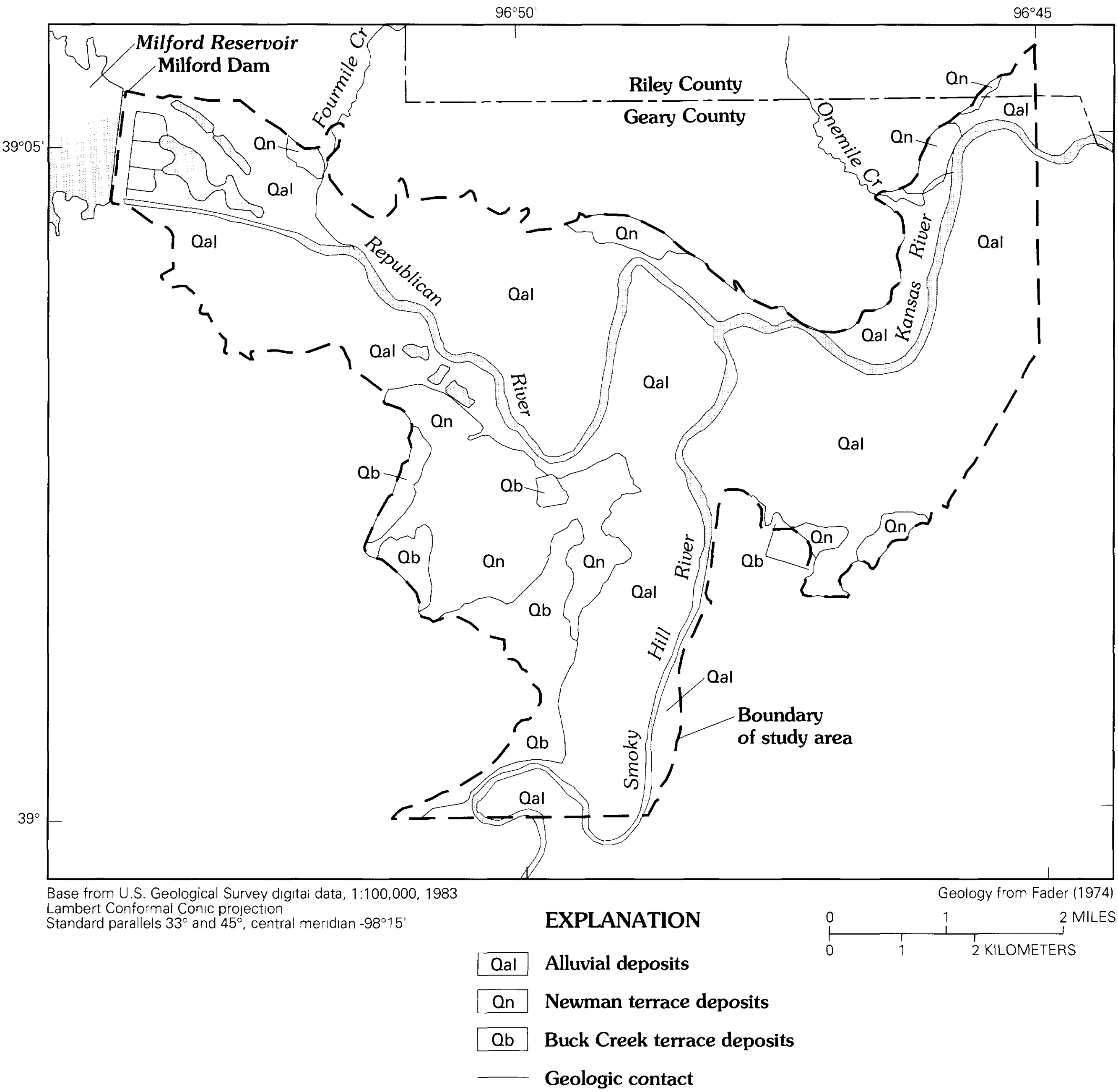
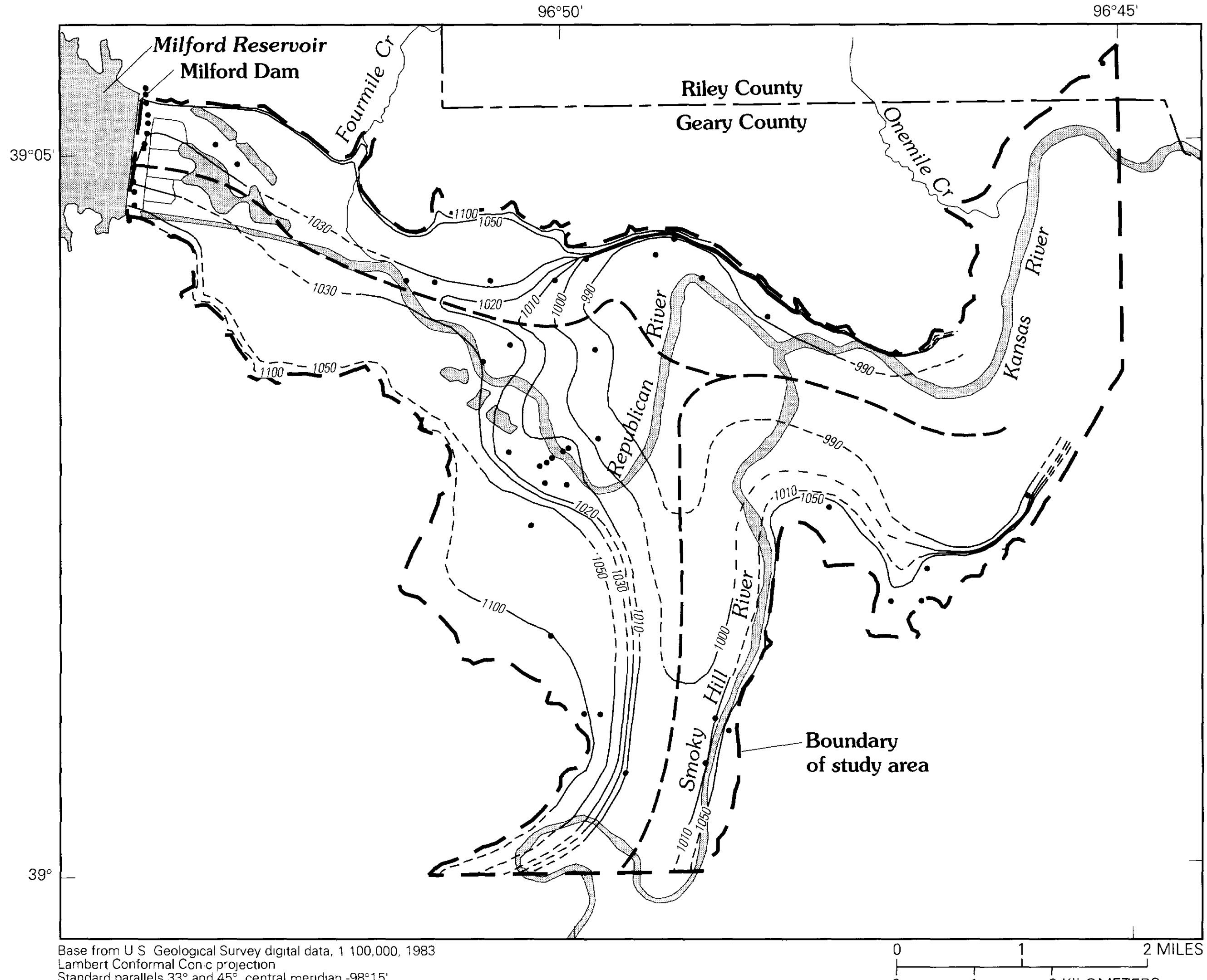


Figure 3. Surficial geology in study area.

these rivers was unregulated before the late 1950's and early 1960's when a series of dams and reservoirs was constructed to help prevent disastrous flooding, such as that which occurred during 1951 (fig. 5) (U.S. Geological Survey, 1952). Except during July 1993, streamflow in the Republican River in the study area has been completely regulated since August 1967 when Milford Dam was completed. Streamflow in the Republican River downstream from Milford Reservoir generally is related to rainfall to the extent that reservoir outflow is matched to reservoir inflows. However, during periods of substantial precipitation or drought, water releases are dictated by reservoir- and river-management needs and may not be related directly to precipitation. During July 1993, extremely large amounts of rainfall and runoff filled Milford Reservoir and caused a maximum flow of about 33,000 ft^3/s (about 0.76 acre-ft/s) over the reservoir's uncontrolled spillway. During the following months, outflow remained large to reduce the volume of water



EXPLANATION

—1050— — **Bedrock-surface contour**—Shows the altitude of the top of the bedrock surface. Dashed where approximately located. Contour interval is variable. Datum is sea level

Bedrock-surface contour—Several contour lines are merged into one line where the bedrock surface is very steep

— — — **Axis of stream channel eroded into bedrock**

• **Borehole or well location**

Figure 4. Bedrock-surface paleotopography (contours are based on borehole data on file with the U.S. Geological Survey in Lawrence, Kansas).

in the reservoir even though precipitation amounts were at or below normal.

Since the completion of Milford Dam in 1967, the Republican River streambed downstream of the dam has degraded. On the basis of rating curves developed for the Republican River below Milford Reservoir gaging station, the stream stage corresponding to a streamflow of 100 ft^3/s decreased by about 9 ft from 1967 to 1993 (fig. 6). Capture of sediment in Milford Reservoir has resulted in sediment-starved conditions downstream of the dam and the consequent erosion of the streambed as the river water picks up and transports available sediment.

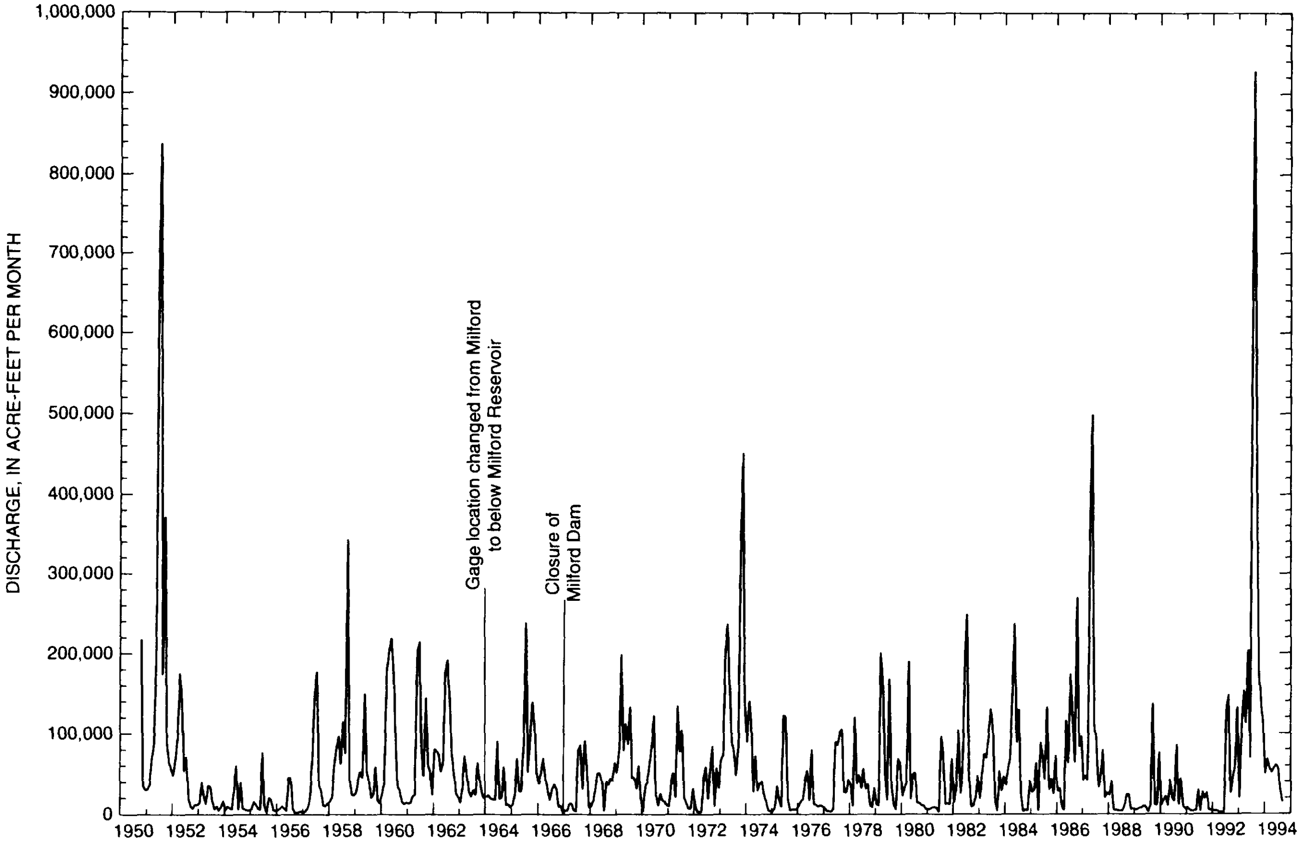


Figure 5. Total monthly discharge computed from daily mean discharge at Republican River at Milford gaging station, October 1950–December 1963, and Republican River below Milford Reservoir gaging station, January 1964–October 1994. The Republican River at Milford gaging station, which was located about 12.6 river miles upstream from the Republican River below Milford Reservoir gaging station, was discontinued in March 1964 because of the construction of Milford Dam.

Streamflow in the Smoky Hill River in the study area is partially regulated. The closest dam (Kanopolis Dam, fig. 1) on the Smoky Hill River is about 180 river mi upstream from the study area.

Ground Water

Ground water in the alluvial and terrace deposits (hereinafter referred to as the alluvial aquifer) is unconfined throughout the study area. Thickness of the saturated zone in the alluvial aquifer ranges from zero at the valley edges to about 60 ft in the channels eroded into bedrock. The mean saturated thickness in the well-field area was about 42 ft during May 1993 and about 37 ft during November 1994. These values were estimated on the basis of measured ground-water levels in USGS observation wells and a mean bedrock-surface altitude of about 1,010 ft above sea level in the well-field area.

Potentiometric-surface maps for May 26–28, 1993, and November 8–9, 1994 (fig. 7), show that ground water in the alluvial aquifer generally flows down the valley in the direction of streamflow and either towards or away from the river. Some contours between the Republican and Smoky Hill Rivers were drawn on the basis of river-water altitudes interpolated between gaging stations. In the vicinity of the Junction City well field, a depression in the potentiometric-surface has formed (fig. 7) as a result of the pumping of the municipal wells. Ground water in the vicinity of the well field flows towards the pumping wells. Three sand pits northwest of the well field have a large water-storage capacity, which affects ground-water flow near the sand pits during periods of changing ground-water levels. When the ground-water level is rising, the water level in the sand pits rises at a slower rate and thus creates a local depression in the potentiometric surface (fig. 7*A*) towards which ground water flows. Conversely, when the ground-water level is declining, the higher water level in the sand pits may

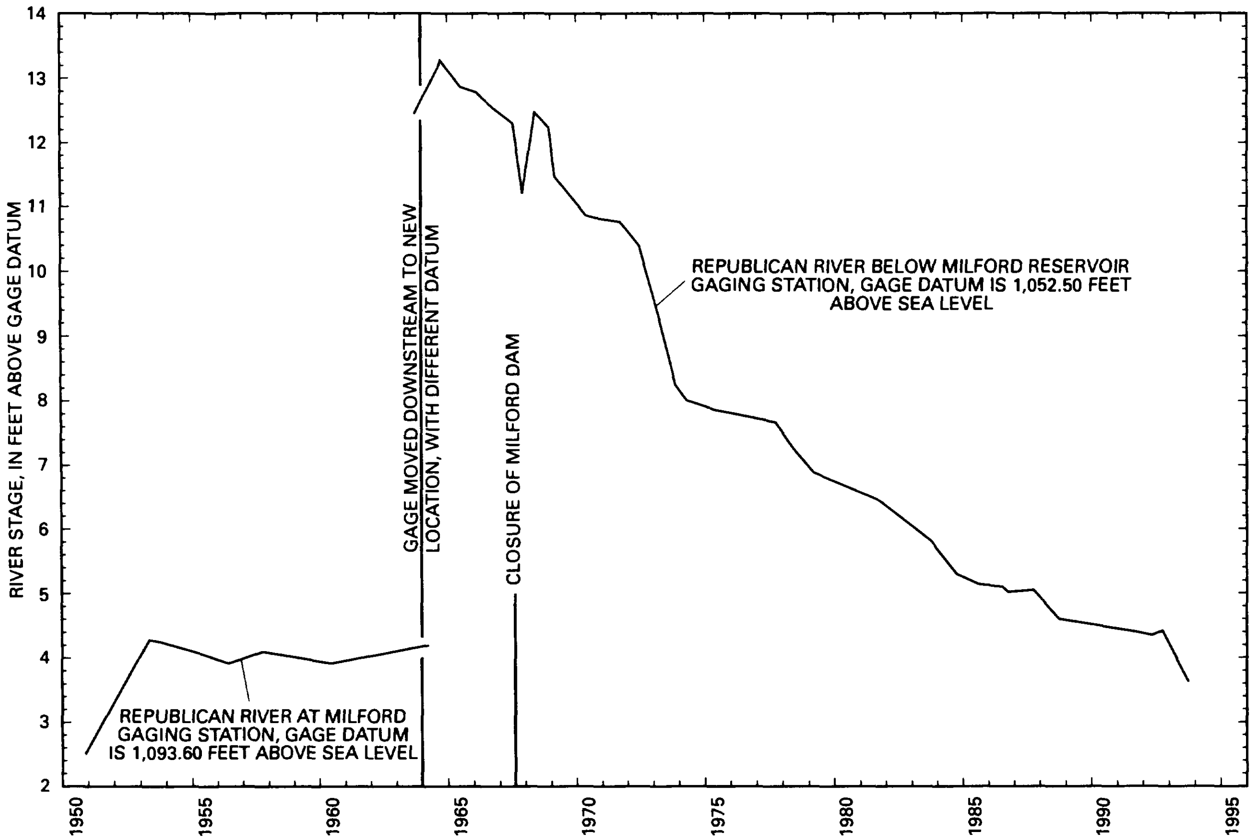


Figure 6. Stage corresponding to 100-cubic-foot-per-second discharge at Republican River at Milford gaging station, November 1950–March 1964, and Republican River below Milford Reservoir gaging station, October 1963–September 1993.

create a local mound in the potentiometric surface away from which ground water flows (fig. 7*B*).

Stream-Aquifer Hydraulic Interaction

Ground-water flow near the streams may be towards or away from the stream depending on the relative difference between stream stage and ground-water levels in the alluvial aquifer adjacent to the stream. When stream stage is higher than the adjacent ground-water level, the stream loses water to the aquifer (fig. 7*A*). When stream stage is lower than the adjacent ground-water level, the stream gains water from the aquifer (fig. 7*B*). If pumping wells near a stream lower the ground-water level below the adjacent stream stage, the stream loses water to the aquifer in the area affected by pumping (fig. 7).

Ground-water-level and stream-stage information recorded during this study indicate that the Republican River and alluvial aquifer near Junction City are an integrated system. Water levels in wells near the Republican River respond very quickly to and match closely changes in stream stage (fig. 8*A*, well USGS–8), whereas water-level changes in wells farther from the river lag stream-stage changes and show less variability (fig. 8*A*, well USGS–6) than water levels in wells closer to the river. Figure 8*B* shows that there is a strong correlation between Republican River water-surface altitudes and ground-water altitudes. Figure 8*B* indicates that the river is the primary factor affecting ground-water levels in the alluvial aquifer adjacent to the river. Ground-water-level changes result from hydraulic adjustments between river water seeping in or out of the aquifer and ground-water flow towards or away from the river. Other factors, such as pumping in the Junction City municipal well field and elsewhere, affect ground-water levels in local areas.

The vertical hydraulic gradient near the well field was determined by comparing hydraulic head in well USGS–9 (adjacent to the Republican River) with head in the Republican River. The mean daily vertical hydraulic gradient for April 1993 through December 1994 ranged from -0.18 to 0.22 and averaged about

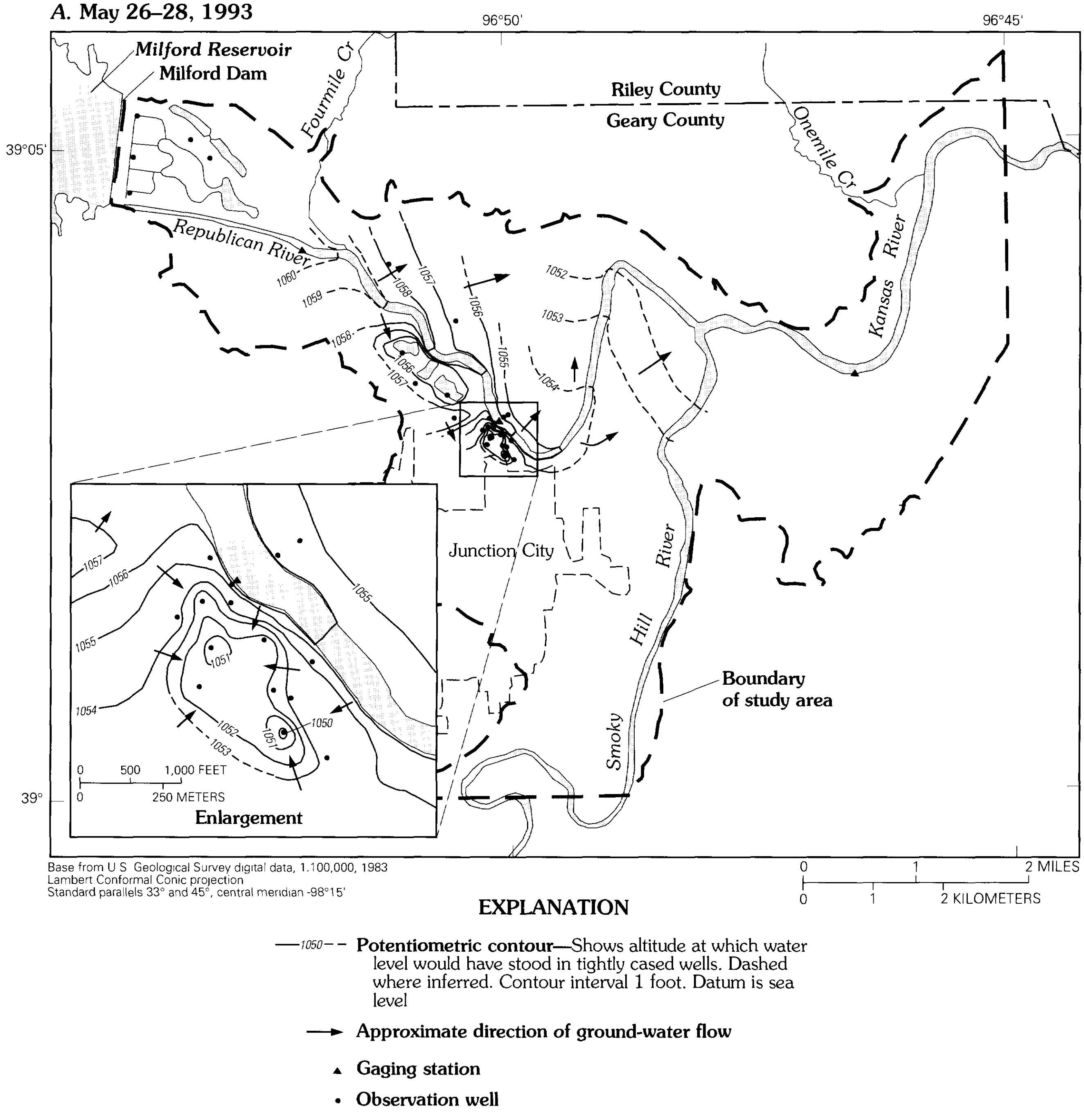
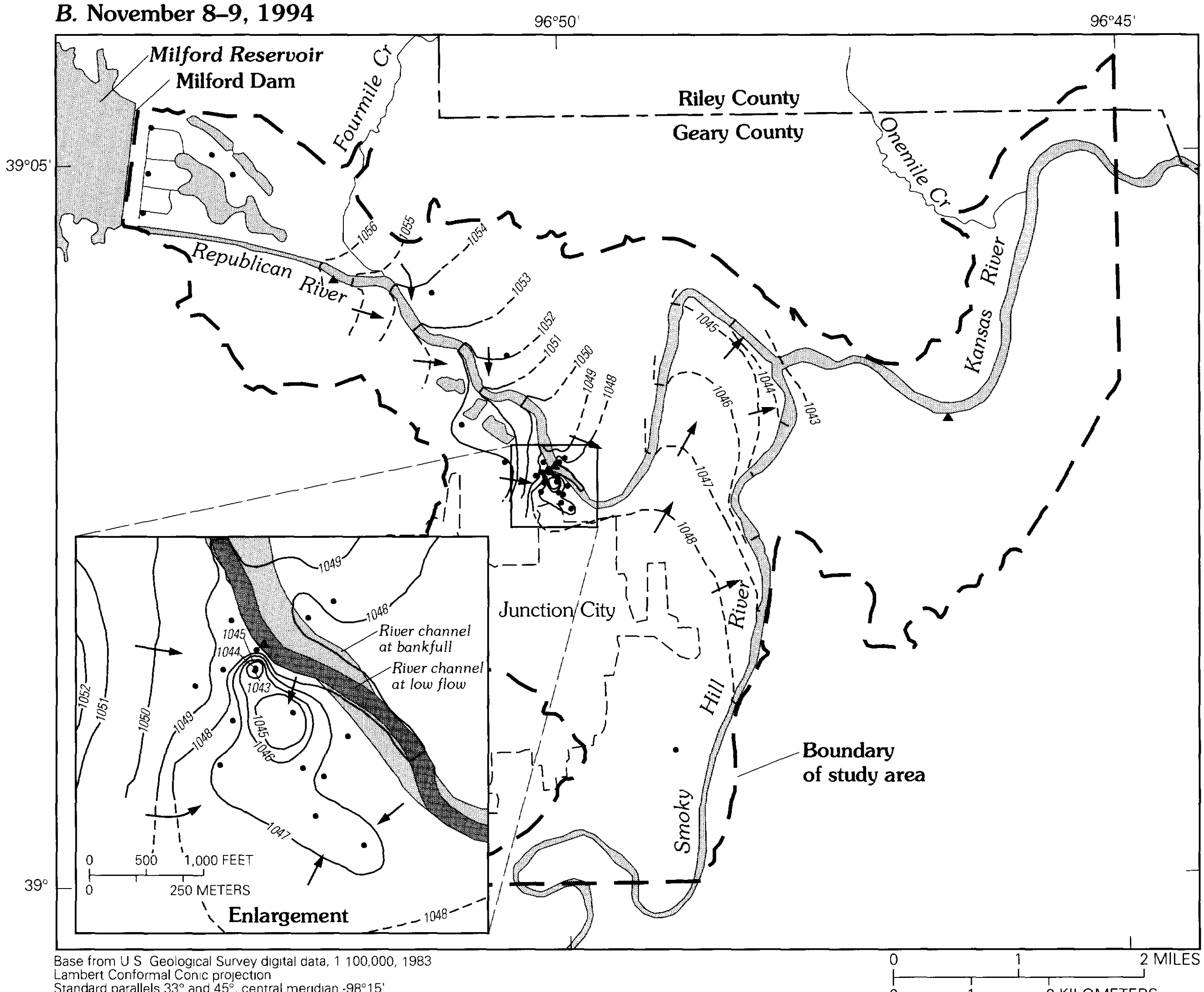


Figure 7. Potentiometric surface in alluvial aquifer for (*A*) May 26–28, 1993, and (*B*) November 8–9, 1994.

0.07, where positive values indicate a downward vertical hydraulic gradient. During May 1993, the mean daily vertical hydraulic gradient ranged from 0 to 0.16 and averaged about 0.09. During November 1994, the mean daily vertical hydraulic gradient ranged from -0.02 to 0.14 and averaged 0.07. The vertical hydraulic gradients calculated at the well field are probably larger than for the rest of the Republican River in the study area because of the drawdown in the well field caused by pumping wells. Well USGS–2 is across the river from the well field, and although water levels in this well were affected by the well field, it probably was more representative than well USGS–9 of water-level conditions in areas along the river away from the well field. During April 1993 through December 1994, the mean daily vertical hydraulic gradient based on

B. **November 8–9, 1994**



EXPLANATION

—1050— — **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells. Dashed where inferred. Contour interval 1 foot. Datum is sea level

Approximate direction of ground-water flow

▲ **Gaging station**

• **Observation well**

Figure 7. Potentiometric surface in alluvial aquifer for (*A*) May 26–28, 1993, and (*B*) November 8-9, 1994—Continued.

data from well USGS–2 and the river ranged from -0.12 to 0.23 and averaged 0.05. Vertical hydraulic gradient values were not calculated for some days in May 1993 and November 1994 because of missing data.

The decline of stream stage because of Republican River streambed degradation (fig. 6) probably has caused a corresponding decline of ground-water levels and a decrease of saturated thickness in the alluvial aquifer. However, there are no long-term water-level records to confirm this. Extended periods of small streamflows and drought, combined with large pumping demands, can have a detrimental effect on Junction City well-field operations, as occurred during the late 1980's (Thomas C. Stiles, Kansas Water Office, oral commun., 1992).

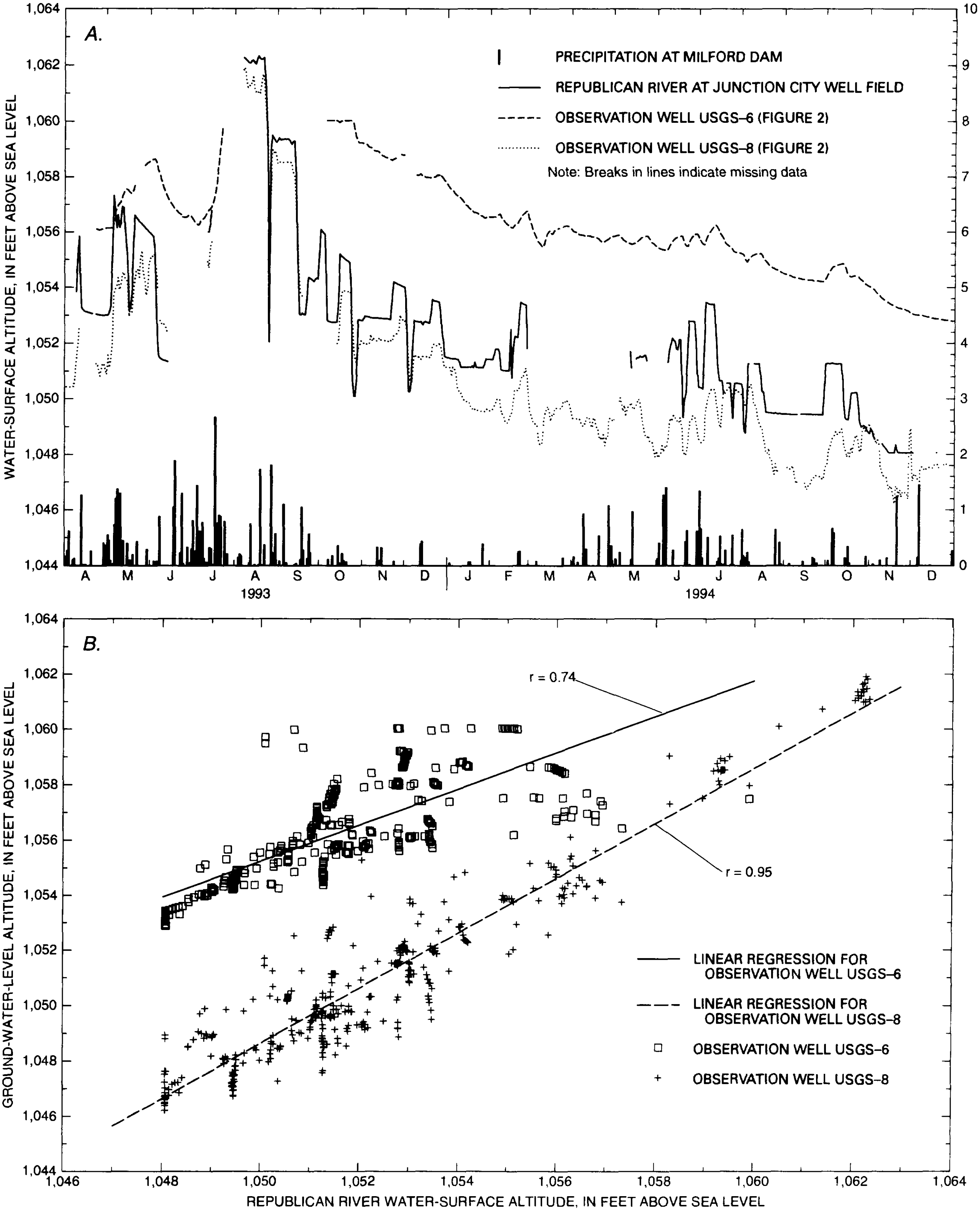


Figure 8. (*A*) Daily precipitation and water-surface altitudes and (*B*) comparison of Republican River water-surface altitudes at Junction City municipal well field and ground-water-level altitudes in observation wells USGS–6 and USGS–8, April 1993–December 1994 (precipitation data for gage at Milford Dam obtained from the National Climatic Data Center, Asheville, North Carolina).

Aquifer Properties

To determine the hydraulic conductivity of the alluvial aquifer near Junction City, three sources of data were used:

(1) In 18 aquifer tests of the Kansas River Valley alluvium, from Manhattan to Kansas City (Fader, 1974), hydraulic conductivity ranged from 200 to 960 ft/d. The mean value was 675 ft/d. The three aquifer tests nearest Junction City reported by Fader (1974) were done near Manhattan. Hydraulic conductivities for those three tests ranged from 750 to 910 ft/d.

(2) During April and May 1975, the ACE conducted a 7-day aquifer test in the Republican River alluvium (U.S. Army Corps of Engineers, 1975). The test site was located near the northeast bank of the river about 1.5 mi northwest of the Junction City municipal well field (fig. 2) . Aquifer-test results indicated that the hydraulic conductivity ranged from about 460 to 1,030 ft/d and averaged about 820 ft/d (U.S. Army Corps of Engineers, 1975).

(3) Transmissivity and hydraulic conductivity were calculated from specific-capacity test data from Junction City municipal wells using the following equations (Lohman, 1979):

$$T = \frac{2.3Q}{4\pi s}\log\left(\frac{2.25Tt}{r^2 S_y}\right), \tag{2}$$

where T is transmissivity, in feet squared per day;
Q is well discharge, in cubic feet per day;
s is drawdown of the water level in the well, in feet;
t is length of the test, in days;
r is the radius of the well, in feet; and
S_y is specific yield, dimensionless;

and

$$K = \frac{T}{b}, \tag{3}$$

where K is hydraulic conductivity, in feet per day; and
b is saturated thickness, in feet.

Specific-capacity data and estimated transmissivity and hydraulic conductivity for wells for which data were available are shown in table 2. The mean hydraulic conductivity from this data is about 360 ft/d.

Table 2. Specific-capacity data and estimated transmissivity and hydraulic conductivity for Junction City municipal wells

[Data from Junction City well-construction records]

Well (fig. 2)	Date of test (month–day–year)	Discharge (cubic feet per day; gallons per minute)	Drawdown (feet)	Length of test (days)	Well radius (feet)	Saturated thickness (feet)	Specific capacity (cubic feet per day per foot of drawdown)	Estimated transmissivity (feet squared per day)	Estimated hydraulic conductivity (feet per day)
CITY–4	7–23–37	192,513; 1,000	11.5	0.25	0.79	43	16,740	14,787	344
CITY–5	10–19–42	197,326; 1,025	16.7	.33	.79	45	11,816	10,364	230
CITY–9	2–4–65	77,390; 402	4.9	.17	.66	45	15,794	13,835	307
CITY–15	2–16–78	231,016; 1,200	9.2	.17	.66	37	25,110	23,012	622
CITY–16	8–10–90	192,513; 1,000	15.0	.25	.66	38	12,834	11,442	301

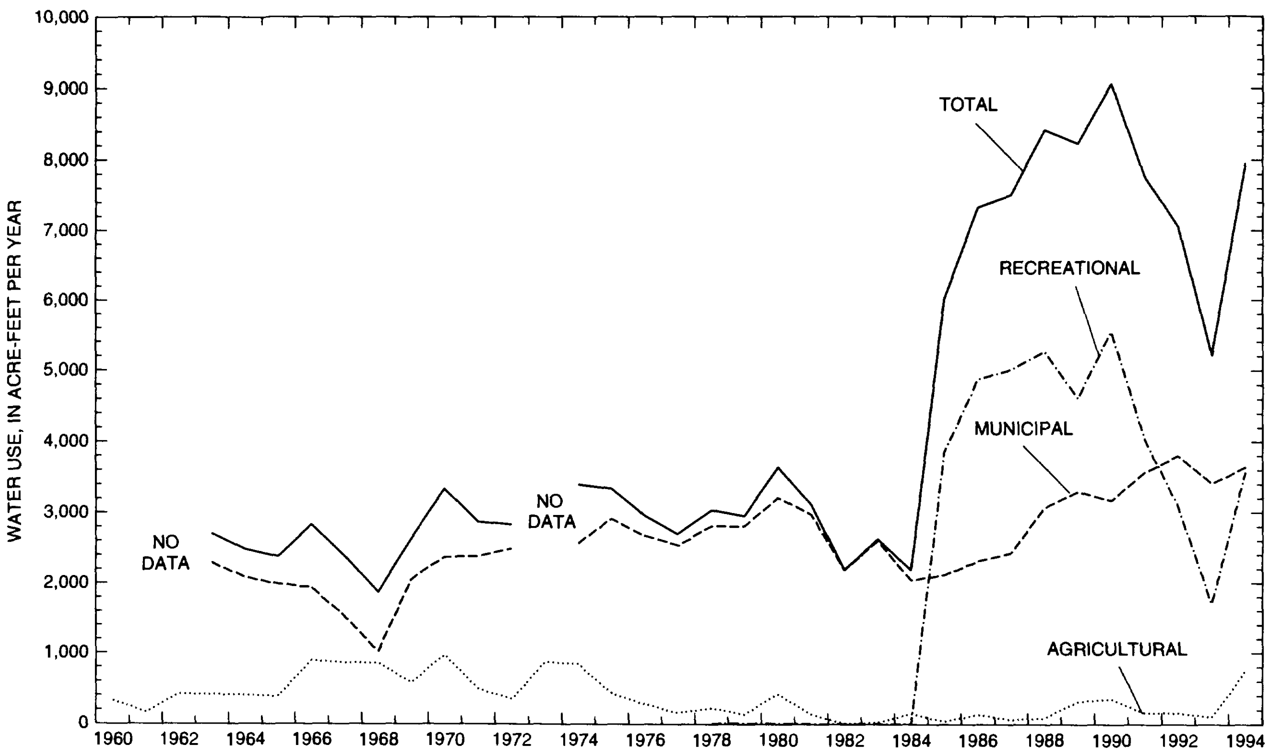


Figure 9. Reported ground- and surface-water use in study area, except for Fort Riley, 1960–94 (data obtained from the Kansas Department of Agriculture, Division of Water Resources, Topeka, Kansas).

Specific yield was assumed to be 0.20 for each analysis of specific-capacity data.

As reported by Fader (1974), specific yield of the Kansas River alluvium from Manhattan to Kansas City ranges from 0.1 to 0.25. Fader (1974) estimated that mean specific yield is 0.15. Specific yield at one location within the study area was calculated to be 0.20 on the basis of data obtained during the ACE aquifer test (U.S. Army Corps of Engineers, 1975).

The vertical hydraulic conductivity for the streambed of the Republican River at the Junction City municipal well field varies from 2 to 9 ft/d as determined at three sites (fig. 2) during this study using a potentiomanometer and seepage meter. Although vertical hydraulic conductivity was not measured for the Smoky Hill River streambed, it was assumed to be similar, in part, to the vertical hydraulic conductivity of the Republican River streambed. Part of the Smoky Hill River channel was rerouted into a new channel (fig. 2) dug in an area where bedrock is near the bottom of the streambed and where sediments are finer (Myers and Bigsby, 1989). Because of the presence of bedrock near the bottom of the streambed and the finer sediments for that part of the stream, the overall vertical hydraulic conductivity of the Smoky Hill River was assumed to be about 1 ft/d.

Water Use

Although historic (1960–94) water use is discussed here, only 1993 and 1994 water-use data were used in ground-water flow simulations. Within the study area water is used primarily for recreational, municipal, and agricultural (irrigation and stockwatering) purposes (fig. 9). A small amount of water is used for industrial purposes in the study area. Ground water is the principal source of water for all but recreational use. Recreational water obtained from surface- and ground-water sources is used primarily to supply a fish hatchery near Milford Dam (fig. 2). Municipal water use was the primary water use from 1963 to mid-1984 and after 1991, but was secondary to recreational use from about mid-1984 through 1991 (fig. 9). Municipal water use increased from about 2,300 to about 3,600 acre-ft/yr between 1963 and 1994. Municipal water use during 1993 was 3,426 acre-ft for all municipal wells in the study area and 3,368 acre-ft for Junction City municipal wells (data from Kansas

Table 3. Maximum allowable pumpage for nondomestic supply wells in study area

[Shaded parts of table indicate that the well or wells associated with DWR permit number is located within the area of the conceptual ground-water flow model south of the Republican River (see fig. 13). More than one well may be associated with a DWR permit number. Data from Kansas Department of Agriculture, Division of Water Resources (DWR), Topeka, Kansas]

Map no. (figs. 2 and 13)	DWR permit number	Maximum allowable pumpage (acre-feet per year)	Use of water
CITY–6, 8, 10, 11, 12, 13, 14, 15, 16, and 17	VGE000200, A00965800, and A02380400 combined	4,664	Junction City municipal
IR–8	A92901000	10	agricultural
IR–5	A00899700	24	agricultural
IR–8	A03259800	93	agricultural
IR–4	A03382300	45	agricultural
IR–3	A03386000	36	agricultural
IR–6	A03911900	1	agricultural
IND–1	A03255000	1	industrial
IND–2	A03783700	27	industrial
IND–3	A04096000	50	industrial

Map no. (fig. 2)	DWR permit number	Maximum allowable pumpage (acre-feet per year)	Use of water
RWD–1	A02715600	151	municipal
RWD–2	A03205200	150	municipal
IR–9	A00442900	200	agricultural
IR–9	A00562000	200	agricultural
IR–1	A01565000	125	agricultural
IR–7	A01873900	102	agricultural
IR–2	A03386100	8	agricultural
IR–2	A04076800	85	agricultural
KWDP–3	A03560700	330	recreation
KWDP–1	A03560800	330	recreation
KWDP–2	A03560900	330	recreation

Department of Agriculture, Division of Water Resources, Topeka, Kansas). Agricultural water use increased during the 1960's from a low of about 200 acre-ft to about 1,000 acre-ft during 1970. During the late 1970's, agricultural water use decreased and, during the 1980's, was generally less than 100 acre-ft/yr. Agricultural water use during 1993 was only about 99 acre-ft, whereas agricultural water use for 1992 and 1994 was about 163 and 743 acre-ft, respectively. Agricultural water use was less during 1993 because of the extremely wet conditions that year and larger during 1994 because of the dryer conditions that year. Most water used for agricultural purposes is pumped from the aquifer during the irrigation season, about June through mid-September. Industrial water use in the study area since 1981 has been less than 6 acre-ft/yr. During 1988–93, industrial water use was zero and during 1994 was 0.7 acre-ft.

All supply wells, except domestic wells, in the study area have been allocated ground water according to K.S.A. 82a.701 through 82a.733 and have been issued water-use permits by DWR. Each permit sets the maximum allowable amount of water that may be pumped from a well or group of wells (table 3). Domestic wells that supply water for household or farmstead use are not required to have a permit.

Within the study area, maximum allowable ground-water pumpage for recreational, municipal, agricultural, and industrial uses are 990, 4,965, 929, and 78 acre-ft/yr, respectively (table 3).

Ground water pumped from wells north of the Republican River is used to supply Fort Riley's municipal, industrial, and other water needs. Historical pumpage from Fort Riley wells is not included in figure 9; however, on the basis of data obtained from Fort Riley, the total pumpage for Fort Riley wells for 1993 was about 3,600 acre-ft.

EFFECTS OF PUMPING ON STREAMFLOW

The effects of well pumping on streamflow depend on several factors, including the hydraulic conductivity of the streambed and aquifer, the saturated thickness and specific storage or specific yield of the aquifer, the distance between the wells and the river, and the well-pumping rate. A decrease in streamflow due to well pumping can be computed using equations from Jenkins (1968) for wells at various distances from a stream (fig. 10). Wells close to a stream generally affect streamflow sooner and to a greater extent than wells farther from a stream (fig. 10), assuming the well pumps were turned on at the same time and the wells were pumped at the same rate. The maximum stream-water depletion, or decrease in streamflow, occurs at some time after the well pumps have been turned off. The delay occurs because the drawdown effects of pumping propagate through the aquifer for a period of time after the well has been turned off and is longer for wells farther from the stream (fig. 10).

A streamflow decrease may not consist entirely of water from a stream (induced infiltration) (fig. 11) but also may consist of ground water that would have become base flow in the stream under a nonpumping hydraulic gradient towards the stream (intercepted base flow), or may consist entirely of intercepted base flow. Jenkins (1968, p. 3) writes:

> "Both during and after pumping, some part, and at times all of stream depletion can consist of ground water intercepted before reaching the stream. Thus, a stream can be depleted over a certain reach, yet still be a gaining stream over that reach. The flow at the lower end of the reach is less than it would have been had depletion not occurred, and less by the amount of depletion."

The stream-water depletion equations (Jenkins, 1968) and the curves shown in figure 10 incorporate the following assumptions:

(1) Transmissivity of the aquifer does not change with time.
(2) The temperature of the stream and aquifer are the same and are constant.
(3) The aquifer is isotropic, homogenous, and semi-infinite in areal extent.
(4) The stream is straight and fully penetrates the aquifer.
(5) Water is released instantaneously from storage.
(6) The well is open to the full saturated thickness of the aquifer.
(7) The pumping rate is steady.

Departure from these assumptions and other factors, such as ground-water recharge from precipitation, lateral ground-water inflow or outflow, or ground-water

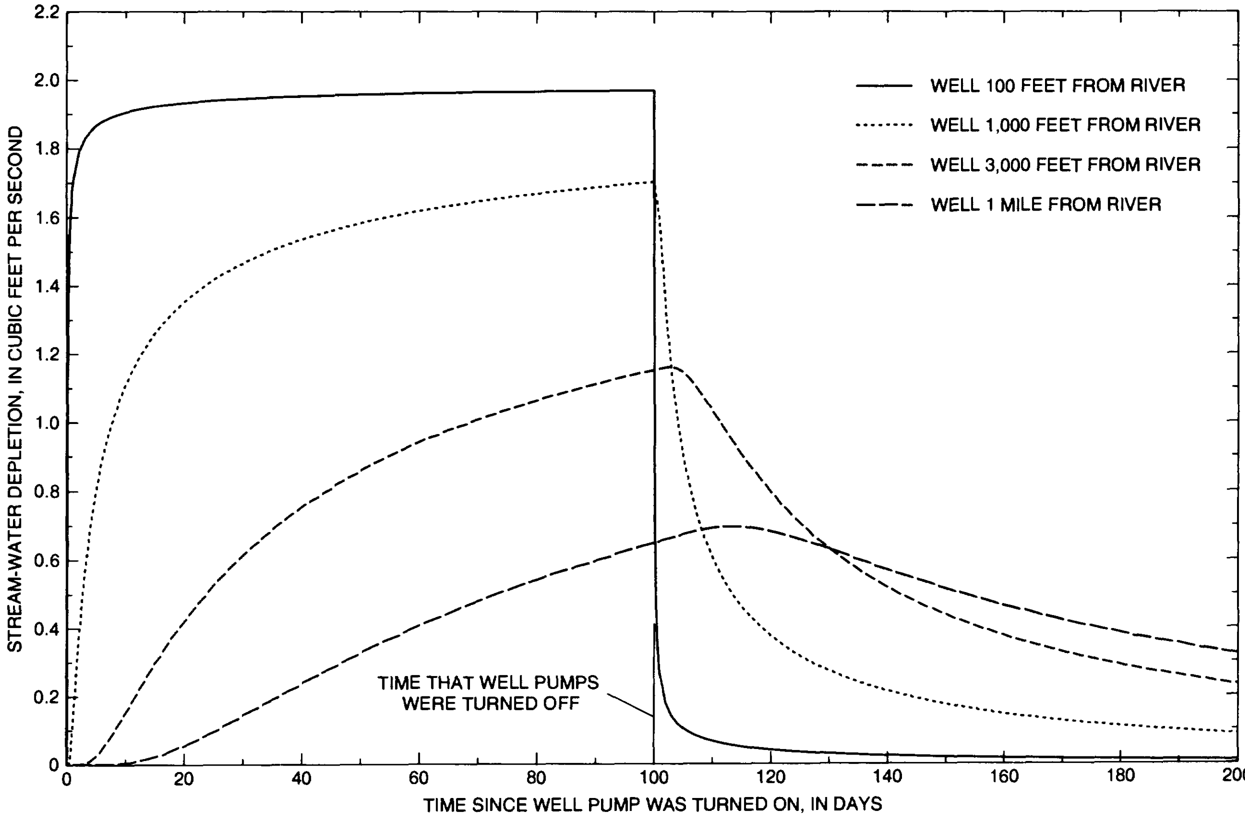
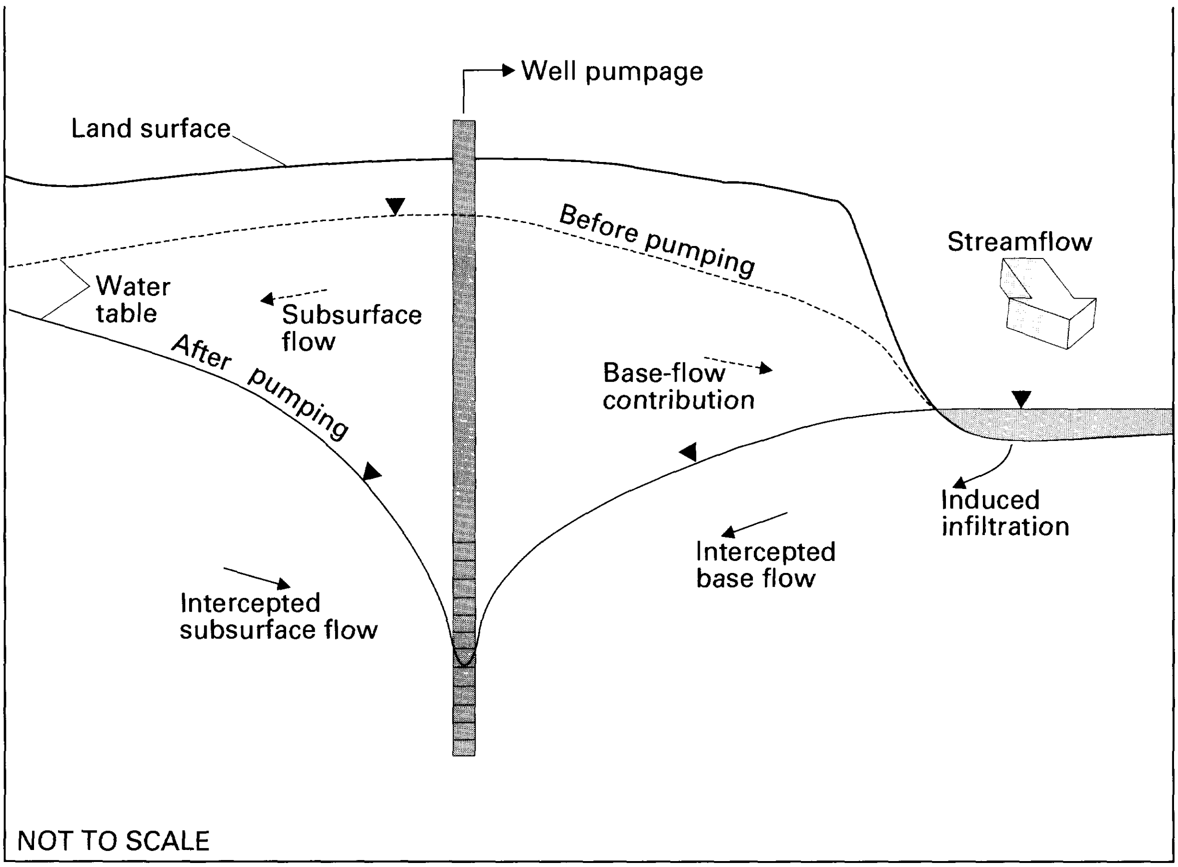


Figure 10. Hypothetical stream-water depletion by pumping wells that are 100, 1,000, and 3,000 feet, and 1 mile from a stream, assuming hydraulic conductivity = 600 feet per day, saturated thickness = 60 feet, specific yield = 0.25, and well-pumping rate = 2 cubic feet per second (about 900 gallons per minute). The well pumps were turned off at 100 days.



Well pumpage = Intercepted subsurface flow + Intercepted base flow + Induced infiltration

Streamflow decrease = Intercepted base flow + Induced infiltration

Figure 11. Ground- and surface-water components that make up well pumpage and streamflow decrease caused by pumping wells.

discharge by evapotranspiration, will cause variations from the calculated stream-water depletion. A full analysis of stream-water depletion and the effects of aquifer recharge and discharge can be made by use of a digital ground-water flow model.

Seepage Surveys

Three seepage surveys were conducted during March, November, and December 1994 to determine streamflow gains or losses in the Republican River near the Junction City municipal well field (fig. 12). All three seepage surveys showed streamflow gains in the reach from the Republican River below Milford gaging station to the well field (seepage-survey site 3 or 5, figs. 2 and 12) and streamflow loss ranging from about 1 to 5 ft^3/s in the vicinity of the well field (seepage-survey sites 3–6 or 5–6, figs. 2 and 12). The probable error (Rantz and others, 1982) in the seepage-survey measurements was about ± 5 percent of the total streamflow (fig. 12). At a ± 5-percent error, the December 22, 1994, measured streamflows at sites 5 and 6 are not significantly different. Measured streamflows at sites 3 and 6 (March 8, 1994) and 5 and 6 (November 8, 1994) are significantly different.

Ground-Water Flow Model

The ground-water flow model for this study was developed in two steps. First, a conceptual model that defined boundaries, recharge, and discharge was developed. Then a digital ground-water flow model was developed to represent the conceptualized system. The recharge and discharge values for the conceptual

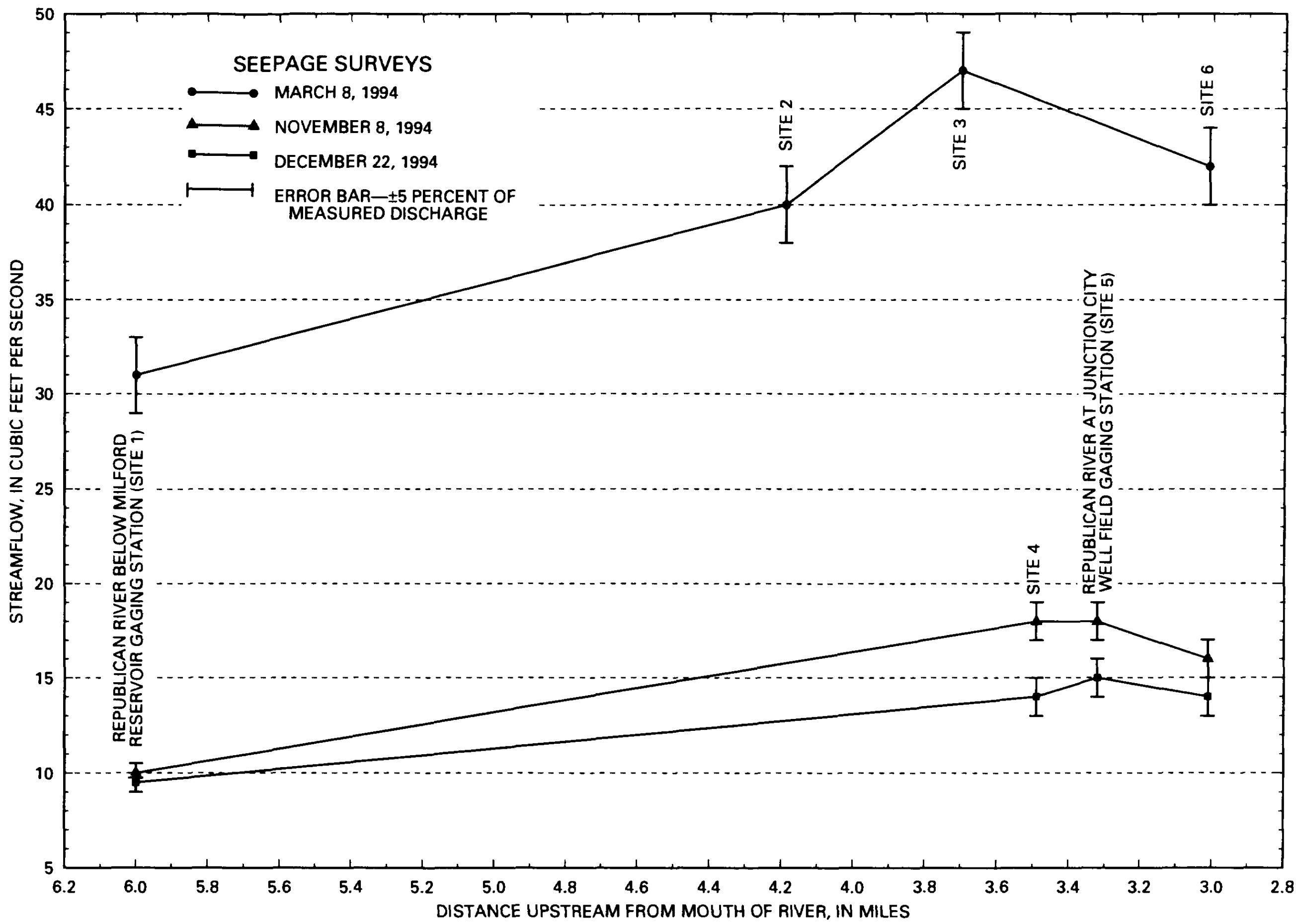


Figure 12. Results of seepage surveys of Republican River, 1994. Seepage-survey sites are located in figure 2.

model were developed independently of the digital model and were used to check the reasonableness of the digital model results.

Conceptual Model

To understand the stream-aquifer system near Junction City, the system was simplified (conceptualized) so that it could be analyzed more readily. The conceptual model area generally conforms to the study area (fig. 2), except that the conceptual model area only extends from the Republican River below Milford Reservoir gaging station on the west to the confluence of the Republican and Smoky Hill Rivers on the east. Within this area, the alluvial aquifer was conceptualized as an unconfined aquifer. The boundaries, recharge to, and discharge from the aquifer are discussed in the following sections.

Boundaries of Aquifer

The alluvial aquifer near Junction City is underlain and bounded on the north and parts of the west and east by relatively impermeable bedrock, generally comprised of shale and limestone. Lateral flow of ground water from bedrock was assumed to be negligible. On the south and part of the east, the Smoky Hill River is the boundary of the study area, where ground-water levels change as river stage changes. On the northwest, lateral inflow from west to east occurs within the aquifer.

Recharge to or Discharge From the Aquifer

Water recharged to the aquifer in the conceptual model area may come from precipitation, subsurface inflow, seepage from streams, and agricultural and urban water applications. The major discharges from the aquifer are municipal pumping, seepage to

Table 4. Water budget for conceptual model area, May 1993 and November 1994 conditions

[All values are in cubic feet per second. -, recharge is less than discharge]

Budget item	May 1993 condition			November 1994 condition		
	Aquifer recharge	Aquifer discharge	Total (recharge minus discharge)	Aquifer recharge	Aquifer discharge	Total (recharge minus discharge)
Recharge from precipitation	14	0	14	2.2	0	2.2
Subsurface inflow (recharge) and outflow (discharge)	3.3	1.9	1.4	.75	.81	-.06
Seepage for Republican River in vicinity of Junction City municipal well field[1]	3.9	0	3.9	2.5	0	2.5
Seepage for Republican River, not including reach near Junction City municipal well field[1]	35	0	35	0	16.5	-16.5
Seepage for Smoky Hill River	8.4	0	8.4	0	4.2	-4.2
Junction City municipal wells	0	4.46	-4.46	0	4.43	-4.43
Fort Riley supply wells	0	4.45	-4.45	0	3.65	-3.65
Agricultural and industrial wells	0	0	0	0	.001	-.001
Aquifer storage[2]	0	54	-54	24	0	24

[1]Average of two methods used to estimate seepage shown for November 1994 condition.
[2]Values rounded to two significant figures.

streams, evapotranspiration, and subsurface outflow. A water budget for the conceptual model area is summarized in table 4. Parts of this discussion focus on May 1993 and November 1994 conditions because these months were selected for digital simulations.

Recharge from precipitation is water that reaches the water table through the unsaturated zone and adds water to the alluvial aquifer. The amount of recharge depends on the rate and duration of precipitation, the rate of potential evapotranspiration, and the moisture capacity of the soil zone. On the basis of a study by Dugan and Peckenpaugh (1985), the computed mean annual ground-water recharge is about 2 to 5 in/yr (6 to 15 percent of the mean annual precipitation at Manhattan) in the mid-Kansas area. There is a close relation between precipitation and recharge, and this relation becomes approximately linear for mean annual precipitation exceeding 30 in. (Dugan and Peckenpaugh, 1985). Mean annual precipitation at Manhattan is 32.88 in. (National Oceanic and Atmospheric Administration, 1993–94). Within the conceptual model area, 11.61 mi^2, mean annual recharge rate from precipitation was estimated to range from 1.71 to 4.28 ft^3/s (2 to 5 in/yr). Recharge may vary depending on seasonal climatic conditions and the activity of plant transpiration and thus may be larger during cool months when there is less evaporation and transpiration and smaller during hot months when there is more evaporation and transpiration. During May 1993 (rainy, cool month) and November 1994 (dry, cool month), precipitation totaled 9.14 and 1.43 in., respectively. Assuming that recharge during these months would be at the high end of the 6- to 15-percent range, the rate of recharge from precipitation within the conceptual model area would have been about 14 ft^3/s for May 1993 and about 2.2 ft^3/s for November 1994 (table 4).

Subsurface inflow to the aquifer in the conceptual model area occurs in the Republican River Valley at the upstream edge of the area. Subsurface outflow from the aquifer in the conceptual model area occurs in the Kansas River Valley at the downstream edge of the area. Subsurface ground-water inflow and outflow rates were estimated using Darcy's equation.

The total subsurface flow is the difference between subsurface inflow and subsurface outflow. Assuming a hydraulic conductivity of 650 ft/d, cross-sectional areas of 368,620 ft^2 (inflow) and 128,480 ft^2 (outflow), and hydraulic gradients of 0.0012 (inflow) and 0.0020 (outflow), the subsurface inflow was about 3.3 ft^3/s, and the subsurface outflow was about 1.9 ft^3/s for May 1993 (table 4). Assuming a hydraulic conductivity of 650 ft/d, cross-sectional areas of 249,480 ft^2 (inflow) and 107,800 ft^2 (outflow), and hydraulic gradients of 0.0004 (inflow) and 0.001 (outflow), the subsurface inflow was about 0.75 ft^3/s, and the subsurface outflow was about 0.81 ft^3/s for November 1994. The total subsurface flow was 1.4 ft^3/s for May 1993 and -0.06 ft^3/s for November 1994.

Seepage between the alluvial aquifer and the Republican and Smoky Hill Rivers depends on river stages, ground-water levels, streambed vertical hydraulic conductivity, and other factors, such as well pumping and agricultural water applications. Two methods were used to estimate the amount of seepage. One method for estimating seepage is based on the use of Darcy's equation. To estimate the seepage for the Republican River in the vicinity of the municipal well field, a river reach about 3,400 ft long near the Junction City municipal well field was selected. The estimated channel width was 220 ft. Assuming a streambed vertical hydraulic conductivity of 5.0 ft/d, a May 1993 vertical hydraulic gradient of 0.090, and a November 1994 vertical hydraulic gradient of 0.070 (see "Aquifer Properties" section), the calculated seepage from the stream in the vicinity of the well field was about 3.9 ft^3/s for May 1993 (table 4) and about 3.0 ft^3/s for November 1994. To estimate seepage for the Republican River not in the vicinity of the well field, a channel length of 27,300 ft, a channel width of 220 ft, a streambed hydraulic conductivity of 5.0 ft/d, and vertical hydraulic gradients of 0.10 for May 1993 and -0.05 for November 1994 were assumed. These vertical hydraulic-gradient values are within the range of values observed for well USGS–2. Calculated seepages were about 35 ft^3/s from the river to the aquifer for May 1993 (table 4) and about 17 ft^3/s from the aquifer to the river for November 1994.

Another method used to estimate seepage was to measure streamflow at two different points along the river. The difference between upstream streamflow and downstream streamflow is the seepage to or from the river between these two points. Results of the seepage survey conducted November 8, 1994, indicate that the seepage to the aquifer in the vicinity of the well field was about 2.0 ft^3/s (fig. 12). The average value for the two methods of seepage calculation is 2.5 ft^3/s (table 4). Upstream from the well field, results of the same seepage survey indicate that the seepage from the aquifer was about 8.0 ft^3/s over a stream reach of 2.68 mi, or about 3.0 ft^3/s per mile. To estimate seepage for the entire Republican River channel in the conceptual model area, it was assumed that the 3.0 ft^3/s per mile seepage rate would be applicable to 27,300 ft of river channel, excluding the 3,400 ft of river channel in the vicinity of the Junction City municipal well field. Thus, seepage to the 27,300 ft of river channel was about 16 ft^3/s on November 8, 1994. The average value for the two methods of seepage calculation is about 16.5 ft^3/s (table 4). Seepage data were not collected during May 1993.

No seepage survey was conducted for the Smoky Hill River. The Smoky Hill River within the model area is about 29,000 ft long. The channel width was assumed to be 250 ft. Assuming a streambed vertical hydraulic conductivity of 1.0 ft/d, a May 1993 vertical hydraulic gradient of 0.10, and a November 1994 vertical hydraulic gradient of -0.05, the calculated seepage from the stream was about 8.4 ft^3/s for May 1993, and the calculated seepage to the stream was about 4.2 ft^3/s for November 1994.

Municipal pumpage data obtained from Junction City include well-pumping rate, hours of operation for each well, and daily discharges for each well. These data indicate that the mean pumping rate for Junction

City municipal wells was 4.46 and 4.43 ft^3/s for May 1993 and November 1994, respectively. The mean pumping rate for 1993 was 4.65 ft^3/s. There were nine municipal wells in operation during 1993. Since late 1994, 10 municipal wells have been in operation.

There are several wells within the conceptual model area that are used to supply water to Fort Riley. Pumping records obtained from Fort Riley indicate that the mean pumping rate for these wells was 4.45 ft^3/s for May 1993, 3.65 ft^3/s for November 1994, and 4.97 ft^3/s for 1993. Fort Riley's water use is not subject to State law, so the wells have not been assigned maximum allowable pumpage amounts.

There are several agricultural and industrial wells in the conceptual model area. Well-permit data show that the maximum allowable pumping rate for these wells is 0.40 ft^3/s or about 287 acre-ft/yr. On the basis of data obtained from DWR, about 0.02 ft^3/s of agricultural water use within the conceptual model area was reported for 1993, and about 0.40 ft^3/s was reported for 1994. Because these relatively small amounts of water were probably used during the June to mid-September irrigation season, and Dugan and Peckenpaugh's (1985) data show that agricultural applications generally do not exceed crop consumptive requirements, agricultural applications probably did not contribute ground-water recharge during May 1993 and November 1994. Industrial water use in the conceptual model area was zero during 1993 and about 0.001 ft^3/s during 1994. For urban water irrigation, it was assumed that application amounts did not exceed vegetation consumptive requirements.

On the basis of the preceding discussion, recharge to the conceptual model area during May 1993 was estimated to be about 65 ft^3/s, and discharge was estimated to be about 11 ft^3/s. For November, recharge was estimated to be about 6 ft^3/s, and discharge was estimated to be about 30 ft^3/s. On the basis of these values, about 54 ft^3/s was going into aquifer storage during May 1993, and about 24 ft^3/s was coming out of aquifer storage during November 1994 (table 4). These values are consistent with high and low river stages for the Republican River during May and November, respectively, in that a high river stage would cause rising ground-water levels and increasing ground-water storage, and the opposite would be true for a low river stage.

Digital Model

A modular, three-dimensional, finite-difference ground-water flow model (MODFLOW) (McDonald and Harbaugh, 1988) was used to simulate the aquifer and the response of the stream-aquifer system. The alluvial aquifer near Junction City was represented in this study by steady-state and transient, one-layer, ground-water flow simulations. For steady-state simulations, the magnitude and direction of ground-water flow, the hydraulic head, and aquifer storage are constant with time. For transient simulations, the magnitude and direction of ground-water flow, hydraulic head, and aquifer storage may change with time.

Geometry and Boundary Conditions

To use this digital model, the aquifer was represented by an array of nodes and associated finite-difference blocks (cells). The finite-difference grid was 53 columns by 71 rows, with varying cell sizes as shown in figure 13. The width of columns is 500 ft for columns 1–16 and 37–53 and 150 ft for columns 17–36. The height of rows is 500 ft for rows 1–24 and 45–71 and 150 ft for rows 25–44. The smallest cells (150 x 150 ft) were located in the Junction City municipal well-field area to provide better spatial resolution in the area of greatest interest and so that only one municipal pumping or observation well was located in each cell. The valley boundary, the boundary of the study area (fig. 13), represents the physical edge of the alluvial aquifer.

Several different kinds of cells represent different boundary or flow conditions (fig. 14). Inactive cells are known as no-flow cells. No-flow conditions occur when the flux across a boundary is zero, such as at an impermeable bedrock boundary or a ground-water flow divide. In the model, no-flow boundary cells were used to represent the physical edge of the alluvial aquifer and an assumed ground-water flow divide under the Smoky Hill River. General cells are active model cells with no specialized boundary conditions. In constant-head cells, the hydraulic head is held constant during simulation stress periods. Constant-head cells represent the hydraulic connection between the adjacent alluvial aquifer and the modeled part of the aquifer. The simulated ground-water system may induce water flow across constant-head boundaries or may discharge water across constant-head boundaries without changing the hydraulic head in the constant-head cell. Simulated flow to or out of these cells is unlimited.

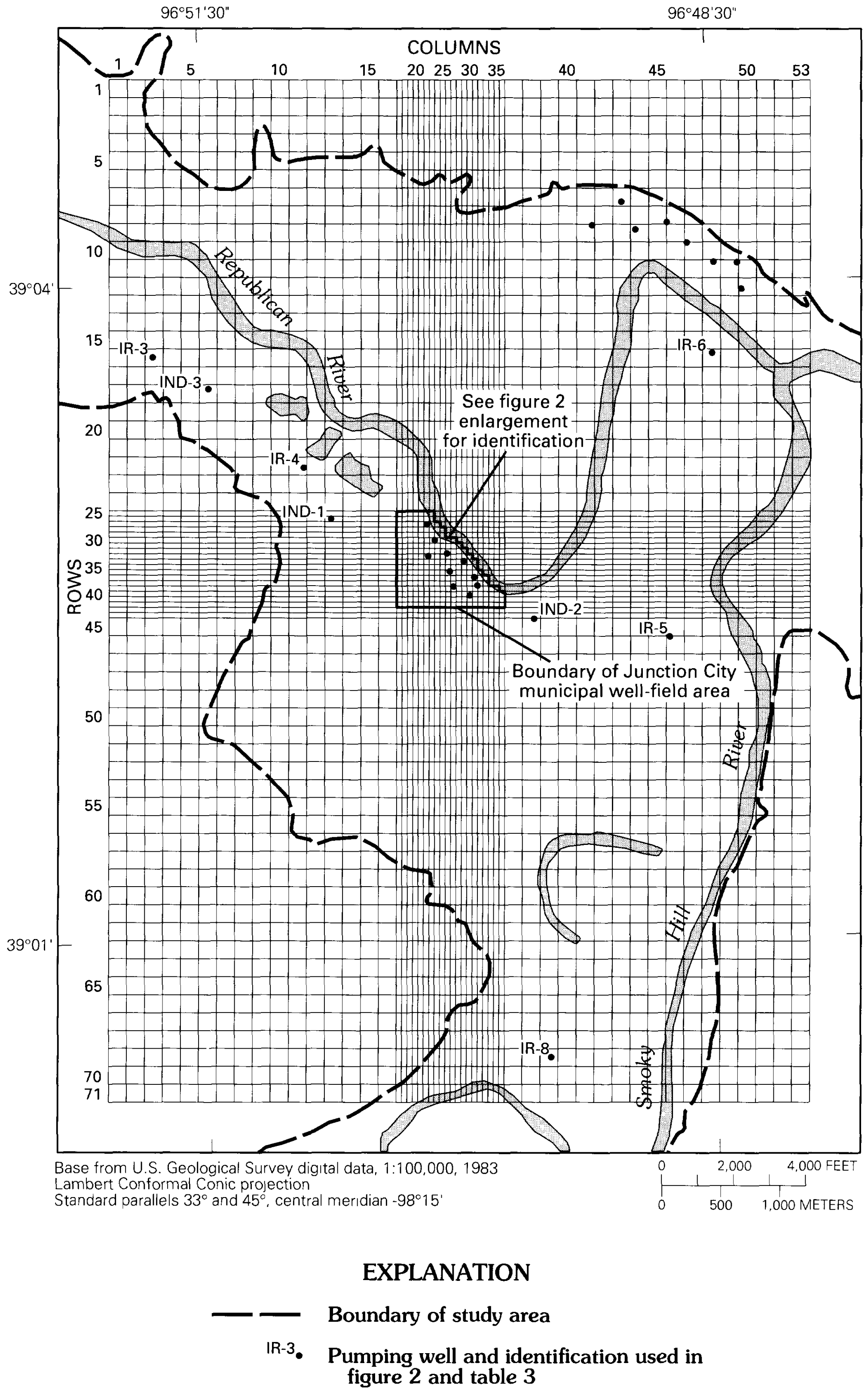
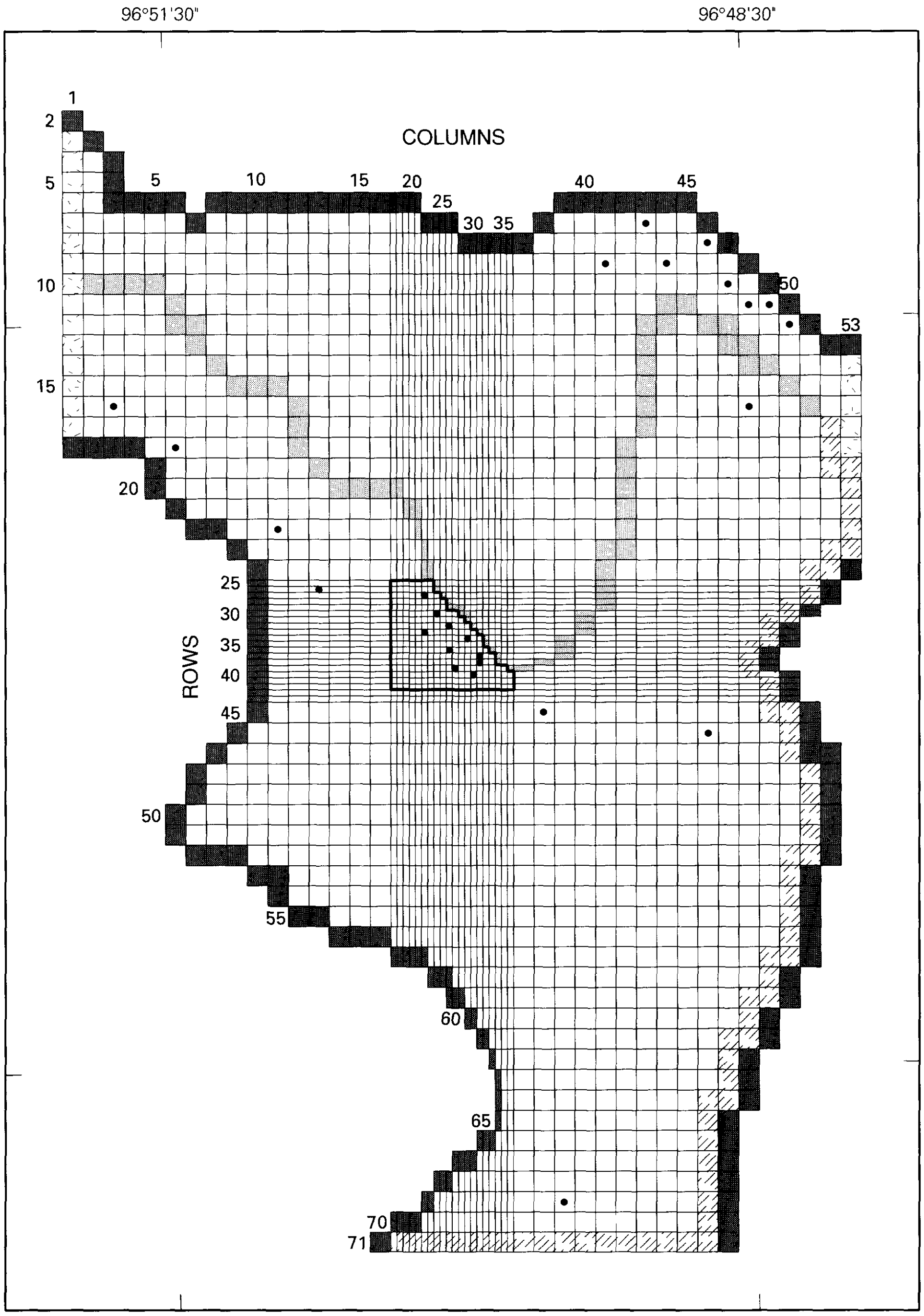


Figure 13. Areal extent, grid spacings, and dimensions of digital model.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Lambert Conformal Conic projection
Standard parallels 33° and 45°, central meridian -98°15'

0 2,000 4,000 FEET
0 500 1,000 METERS

EXPLANATION

- **No-flow cell**
- **General cell**
- **Constant-head cell**
- **River cell (Smoky Hill River)**
- **Stream cell (Republican River)**
- **Pumping cell**—Wells shown in figure 13 are positioned at the center of the model cell nearest their actual location
- **Boundary of Junction City municipal well-field area**

Figure 14. *Digital model cells and boundary conditions.*

Both river and stream cells are active cells that simulate water flow through the streambed between the rivers and streams and the alluvial aquifer. The difference between river and stream cells is that, for river cells, seepage between the stream and aquifer is calculated on the basis of constant stream-stage values provided by the model user, and streamflow is not determined or tracked from cell to cell. For stream cells, streamflow is determined and tracked from cell to cell and is used to calculate stream stage and streamflow gain or loss for each cell (Prudic, 1989). In figure 14, river cells are used to represent the Smoky Hill River, and stream cells are used to represent the Republican River. Streamflow gain or loss calculated by the model for stream cells was used to determine the effects of pumping wells on streamflow in the Republican River.

Pumping cells are active cells that allow simulated pumpage out of the aquifer at these cell locations. In the model, they were used to simulate pumpage from municipal, Fort Riley supply, agricultural, and industrial wells. Simulations of pumpage provide results for these cells as if all pumping wells within the cell were combined into one well located at the center of the cell.

Aquifer Properties

To use a digital model, aquifer properties are assigned to each model cell. For a one-layer, unconfined, steady-state model of the flow system, the values of hydraulic conductivity, vertical hydraulic conductivity of the streambed (where present), and the altitude top of the bedrock surface underlying the aquifer are needed for each cell. For a one-layer, unconfined, transient model of the flow system, specific yield also is needed. The ranges of values of these properties are discussed in the earlier "Aquifer Properties" section. To simplify the model, hydraulic properties were assumed to be relatively uniform within the area. In the model, the hydraulic conductivity was 650 ft/d for the model cells north of the Republican River and 550 ft/d for the model cells south of the Republican River; the specific yield was 0.20 for all cells. A streambed vertical hydraulic conductivity of 2 ft/d was used for the reach of the Republican River upstream from the municipal well field, and 5 ft/d was used for the remaining part of the Republican River. A streambed vertical hydraulic conductivity of 1 ft/d was used for the Smoky Hill River. These values were derived through the calibration process (see "Calibration of Model to May 1993 Conditions").

Types and Locations of Stresses

Several kinds of stresses were simulated by MODFLOW for the digital model. Stresses, as used in this report, are forces external to or that act upon the ground water in an aquifer and affect ground-water levels and movement. These stresses include pumpage for municipal, Fort Riley supply, agricultural, and industrial uses, recharge from precipitation, stream stages resulting from streamflows in the Republican River, and specified stream stages for the Smoky Hill River.

The pumping cells where wells are simulated in the model are shown in figure 14. The number of wells in operation and the amount of pumpage for each well change with time. In this study, the daily pumpage reported for May 1993 (fig. 15*A*) and November 1994 (fig. 16*A*) was used for calibration of and verification of the model, respectively.

Precipitation was assumed to be uniformly distributed over the entire modeled area. Daily precipitation values observed at Milford Dam and used for model calibration and verification are shown in figures 15*B* and 16*B*. The recharge rate for May 1993 and November 1994 was assumed to be 15 percent of precipitation, 9.14 and 1.43 in., respectively.

In the model, the Republican River was represented by stream cells and the Smoky Hill River by river cells (fig. 14) to simplify interpretation of water budgets. The daily mean streamflows measured at the Republican River below Milford Reservoir gaging station (figs. 15*C* and 16*C*) and the daily mean stage measured at the Republican River at the Junction City well field gaging station were used for model calibration and verification. The slopes of the water-surface profile for the Republican River were estimated on the basis of river stages observed at the Republican River below Milford Reservoir, the Junction City well field, and the Kansas River at Fort Riley gaging stations. The slopes can change with river stage. The calculated water-surface slope for 1993 through 1994 averaged 0.0005 for the Republican River upstream from the well field and 0.0004 for the Republican River downstream from the well field. The nearest gaging station on the Smoky Hill River is about 40 mi upstream of the study area. A slope of 0.00033 for the Smoky Hill River was estimated from a 7 1/2-minute USGS topo-

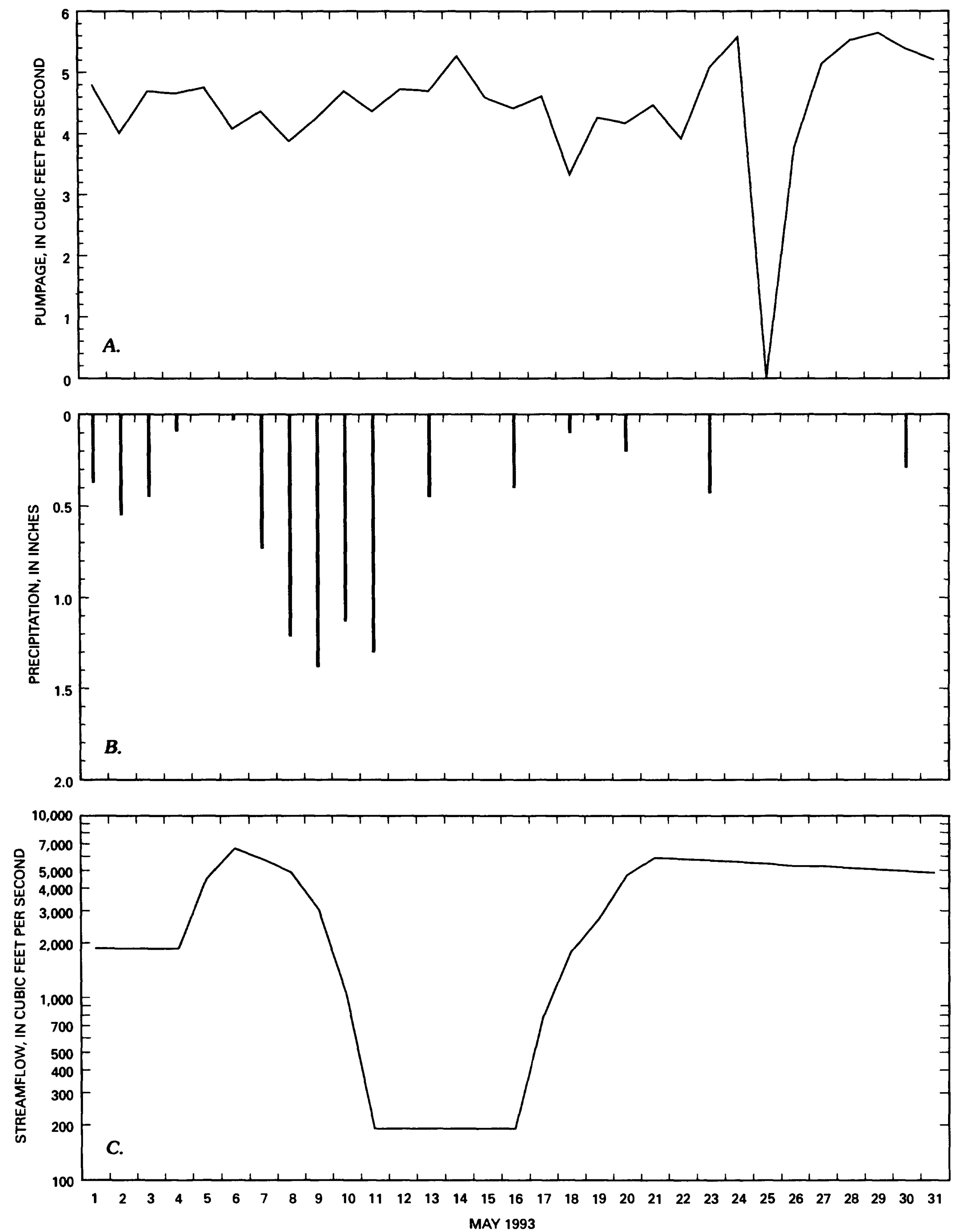


Figure 15. Measured daily (*A*) pumpage from Junction City municipal well field (data from Junction City), (*B*) precipitation at Milford Dam (National Oceanic and Atmospheric Administration, 1993–94), and (*C*) streamflow for Republican River below Milford Reservoir gaging station, May 1–31, 1993.

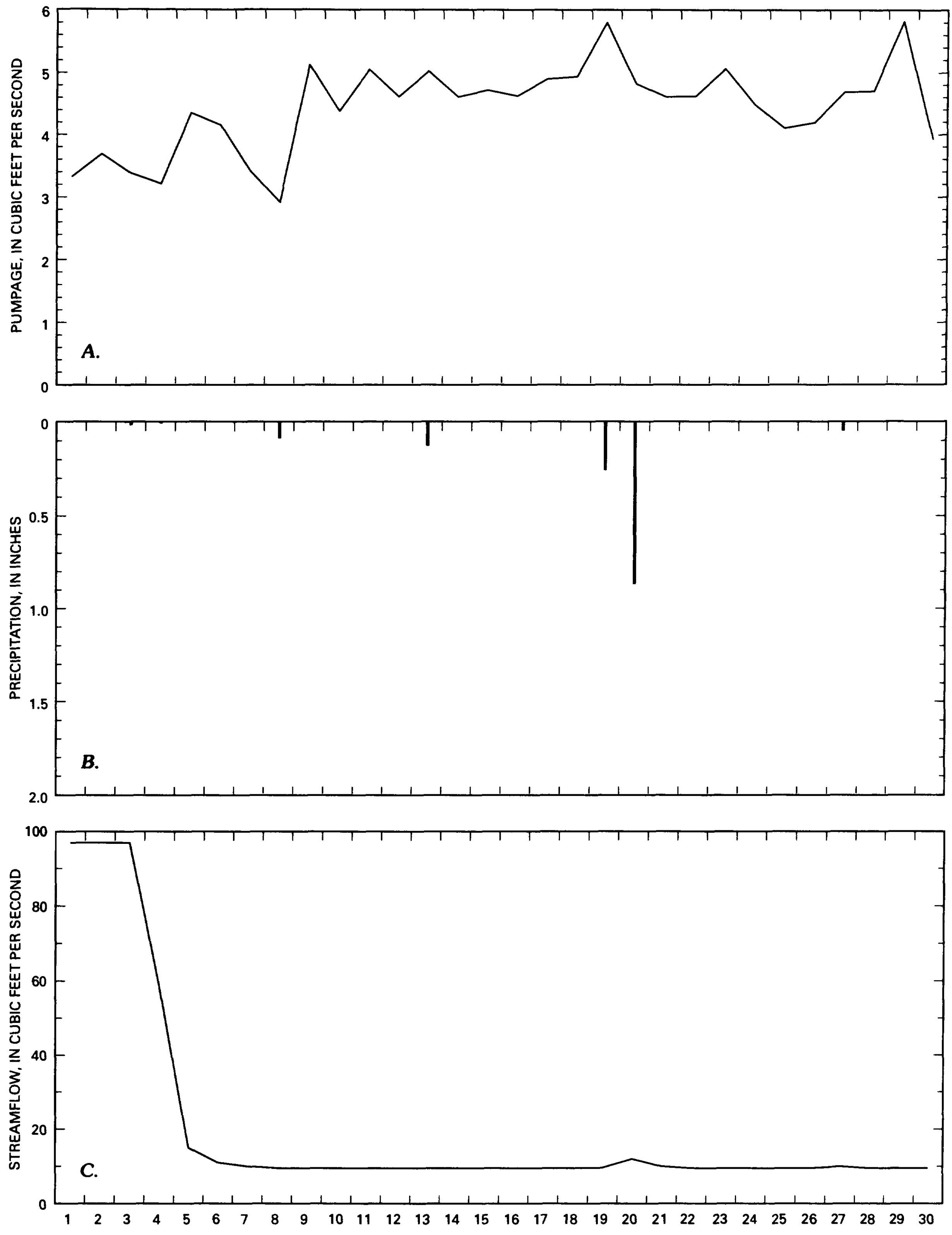


Figure 16. Measured daily (*A*) pumpage from Junction City municipal well field (data from Junction City), (*B*) precipitation at Milford Dam (National Oceanic and Atmospheric Administration, 1993–94), and (*C*) streamflow for Republican River below Milford Reservoir gaging station, November 1–30, 1994.

graphic map. Streambed thickness was assumed to be 1 ft.

Calibration of Model to May 1993 Conditions

To use the model as a simulative tool for the stream-aquifer system near Junction City, it was necessary to demonstrate that the model was capable of reproducing measured hydraulic heads and fluxes (that is, model calibration). Model calibration was accomplished by identifying a reasonable set of aquifer properties, boundary conditions, and stresses such that simulated heads and fluxes matched measured values within an acceptable range of error. Several comparisons were made during the calibration process among measured and simulated potentiometric surfaces, river water-surface altitudes, and ground-water altitudes for selected observation wells.

In this study, the model-calibration process involved numerous transiant simulations of May 1993 conditions using 1-day time steps in which values of hydraulic conductivity, specific yield, streambed vertical hydraulic conductivity, and recharge were adjusted within reasonable limits. The initial hydraulic-conductivity values used in the model were 500 ft/d north of the Republican River and 300 ft/d south of the river. Final values, arrived at through trial and error, were 650 ft/d north and 550 ft/d south of the river. The initial specific yield used was 0.20. Other values were tried, but 0.20 gave the most satisfactory results. Values of streambed vertical hydraulic conductivity used during model calibration ranged from 1 to 9 ft/d for both the Republican and Smoky Hill Rivers. Final values arrived at through trial and error were 2 ft/d for the Republican River upstream from the well field, 5 ft/d for the Republican River from the well field downstream to the confluence with the Smoky Hill River, and 1 ft/d for the Smoky Hill River. A larger vertical hydraulic conductivity at and downstream from the well field could be considered a result of the river having eroded down into coarser sediments than is the case farther upstream. Recharge was varied during calibration from 10 to 20 percent of precipitation, but 15 percent of precipitation gave the most satisfactory results.

Determination of Initial Hydraulic Heads

For the transient simulation of May 1993 conditions, initial hydraulic heads were specified for each model cell in a two-step process. First, a steady-state simulation using the monthly mean precipitation, streamflow, and pumping rates for April 1993 was used to specify a set of starting heads. Second, these heads were manually adjusted up or down in local areas to more closely match measured heads in observation wells and to minimize aquifer-storage changes resulting from differences in hydraulic heads generated by the steady-state and transiant simulations.

Comparison of Measured to Simulated Potentiometric Surfaces, River Water-Surface Altitudes, and Hydraulic Heads

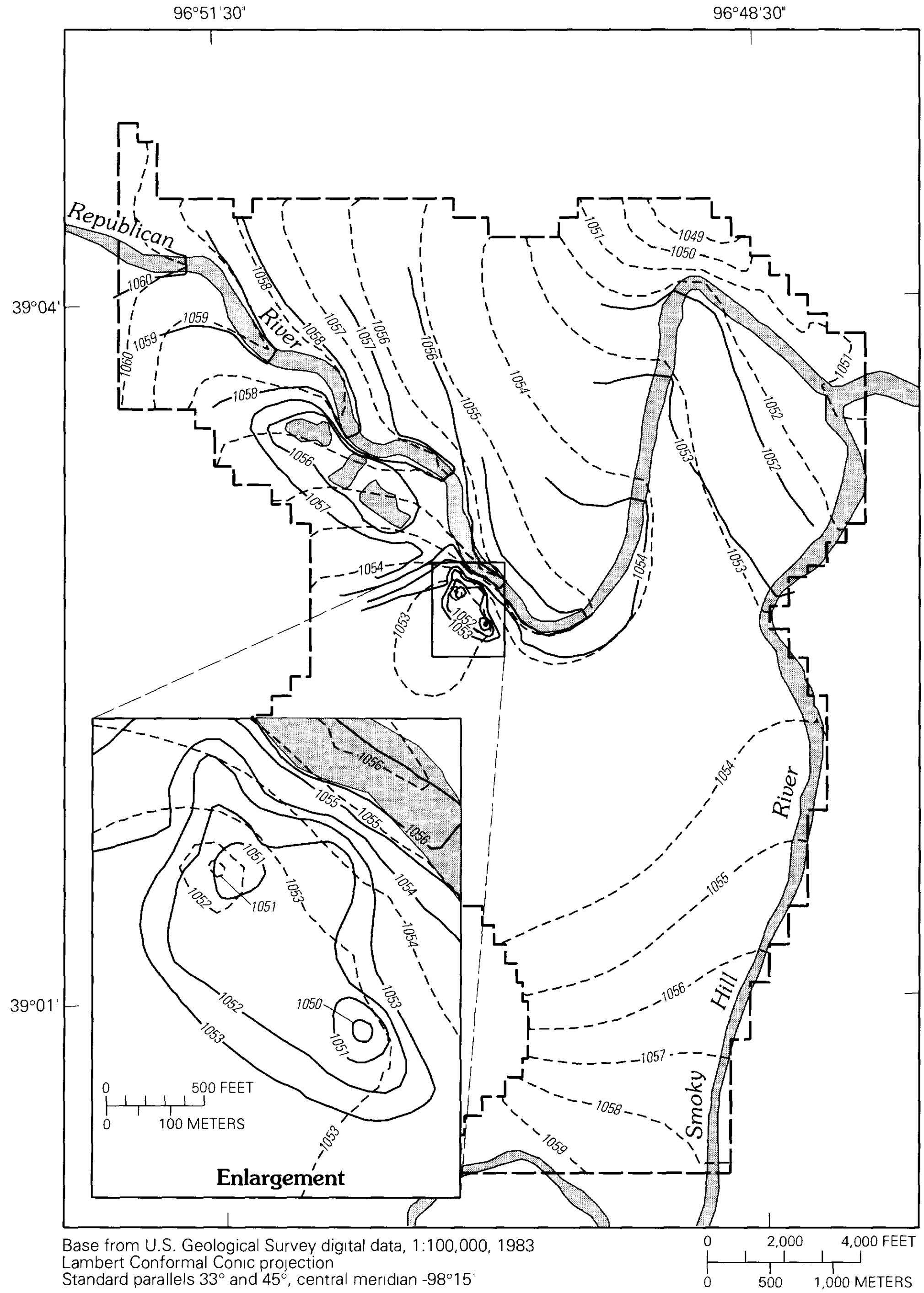
Several comparisons were made during the calibration process among measured and simulated potentiometric surfaces (fig. 17), measured and simulated river water-surface altitudes (fig. 18), and the measured and simulated ground-water altitudes for selected observation wells (fig. 19). Values for the principal model parameters yielding the most satisfactory results in characterizing the stream-aquifer system are summarized in table 5. In the Junction City well field, positional differences between measurement-based and simulation-based potentiometric contours probably result because the model simulates well pumping at the center of a model cell rather than at the actual well location. In the model, pumping was simulated as a daily total value averaged over 24 hours and is evenly distributed over the area of a model cell, whereas, in reality, pumping may only have occurred for a few hours and at a point location within the model cell. This means that simulated drawdown was less than in reality because a smaller pumping rate was simulated and was spread out over a larger area. Also, differences between potentiometric contours may result from day-long simulation of pumping, whereas the pump may actually have been off when the water level was measured. The differences between measured and simulated ground-water altitudes can be expressed as the root-mean-square error (RMSE), which is given by:

$$RMSE = \left(\frac{1}{31} \sum_{i=1}^{31} (\hat{Z}_i - Z_i)^2 \right)^{\frac{1}{2}} , \qquad (4)$$

where Z_i is the measured ground-water or surface-water altitude, in feet above sea level;

$\hat{Z}_i$ is the simulated ground-water or surface-water altitude, in feet above sea level; and

i is the day index.



EXPLANATION

—1050— **Potentiometric contour from measured data**—Shows altitude at which water level would have stood in tightly cased wells. Contour interval 1 foot. Datum is sea level

– – 1050 – – **Potentiometric contour from simulation**—Shows simulated altitude at which water level would have stood in tightly cased wells. Contour interval 1 foot. Datum is sea level

— — — **Boundary of active modeled area**

Figure 17. Measurement-based and simulation-based potentiometric surfaces for May 25–26, 1993.

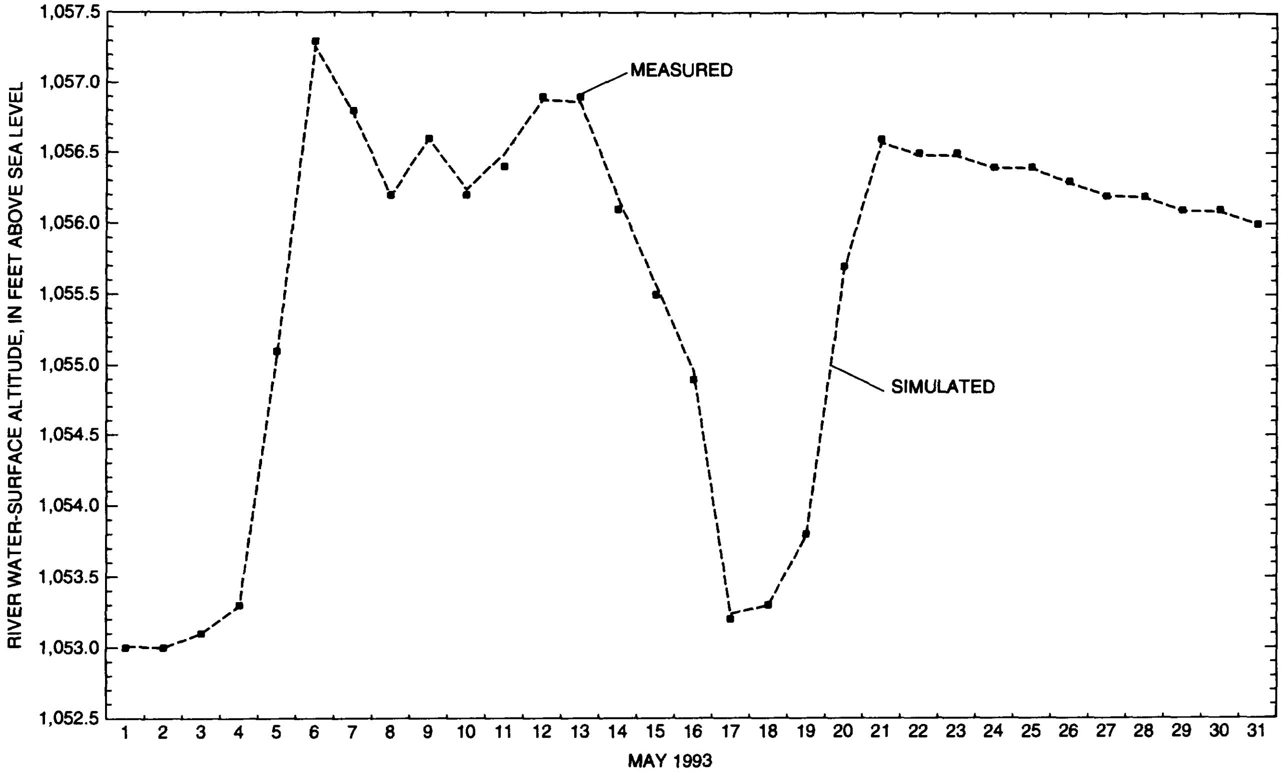


Figure 18. Measured and simulated daily mean river water-surface altitudes for Republican River at Junction City municipal well field, May 1–31, 1993.

In general, the simulated river water-surface altitudes match well with the measured ones, with an RMSE of about 0.04 ft. Simulated daily mean ground-water altitudes match measured ground-water altitudes well, with a maximum RMSE of 0.91 ft (table 6).

Comparison of Simulated and Conceptual Water Budgets

A water budget for the entire model area for the simulation of May 1993 conditions is given in table 7. As shown in table 7, both Republican and Smoky Hill River water seeped into the aquifer to partially offset well pumpage and a net increase in aquifer storage (shown as a negative number in table 7 because water in storage is considered to be an outflow from the digital and conceptual models). Table 7 also shows a comparison between the simulated and conceptual budgets. Except for Republican River seepage and aquifer storage, the simulated and conceptual differences between recharge and discharge are similar (table 7). The conceptual seepage for the Republican River is larger because it was calculated assuming a streambed hydraulic conductivity of 5 ft/d, whereas, in the transient simulation, part of the streambed was simulated having hydraulic conductivity of 1 ft/d and part was simulated at 5 ft/d. The conceptual aquifer storage is smaller than the simulated value because it was calculated on the basis of the other budget terms; it had to be smaller to balance out the larger Republican River seepage value.

Simulated Streamflow Decrease Induced by Municipal Well Pumping

The model, using climatic conditions of May 1993 (fig. 15), was used to simulate the streamflow decrease in the Republican River induced by pumping of Junction City municipal wells and the consequential effects on ground-water levels. Two simulations were conducted, one with and one without pumping.

The daily mean streamflow decrease for with-pumping and without-pumping simulations (fig. 20*A*) shows that pumping increased the amount of streamflow loss. The monthly mean streamflow decrease was 2.16 ft^3/s without pumping and 5.19 ft^3/s with pumping. Figure 20*B* shows the total streamflow decrease and the induced infiltration and intercepted base flow resulting from pumping. The monthly mean total streamflow decrease was 3.03 ft^3/s, and the monthly mean induced infiltration and intercepted

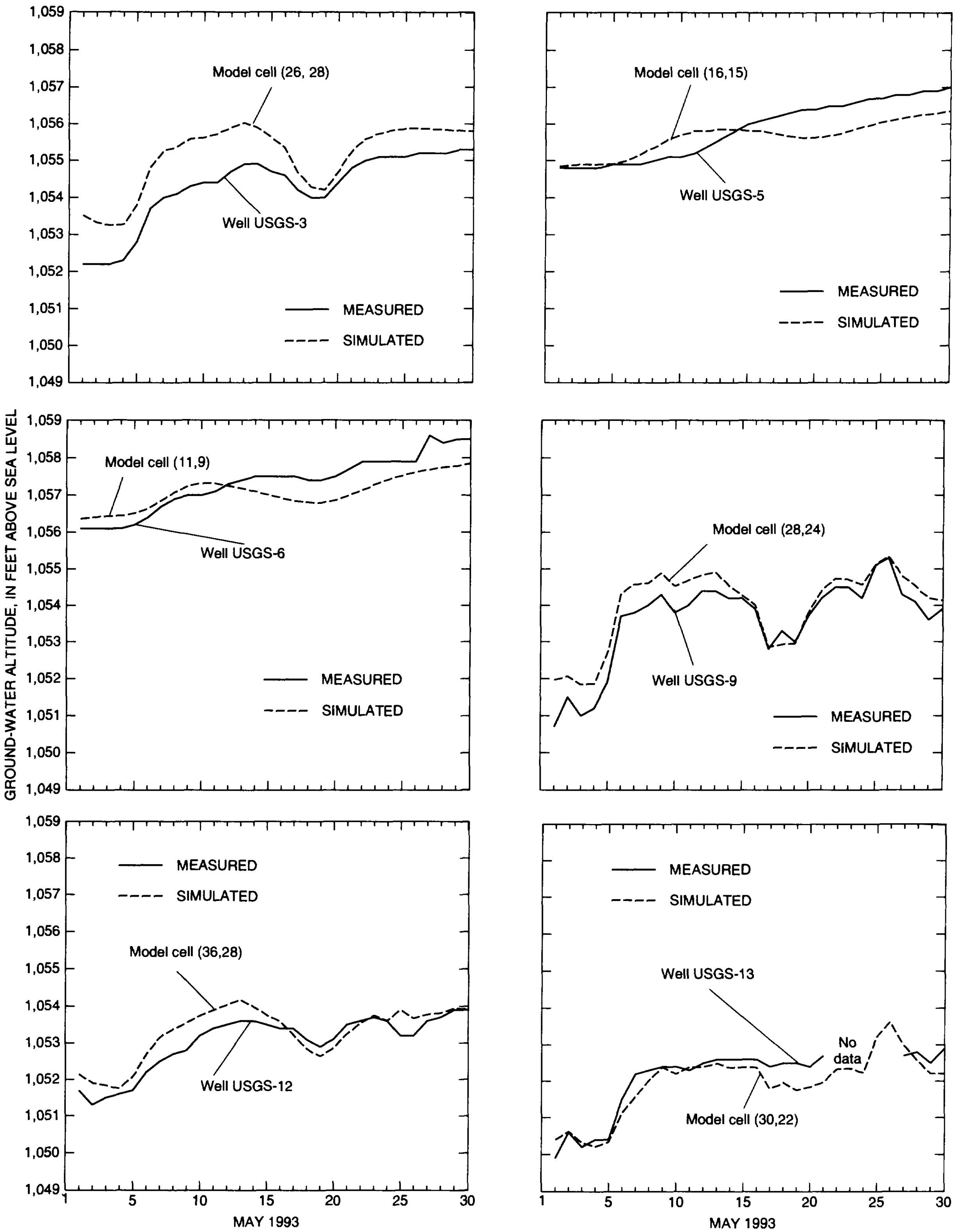


Figure 19. Measured and simulated daily mean ground-water altitudes for selected observation wells in model area, May 1–31, 1993.

Table 5. Calibrated model parameters

Parameter	Value
Aquifer hydraulic conductivity	
North of the Republican River	650 feet per day
South of the Republican River	550 feet per day
Specific yield	0.20
Recharge rate	15 percent of precipitation
Streambed vertical hydraulic conductivity	
Republican River	2 to 5 feet per day
Smoky Hill River	1 foot per day
Streambed thickness for Republican and Smoky Hill Rivers	1 foot

Table 6. Difference between measured and simulated daily mean ground-water altitudes, May 1993

[Values are given in feet. RMSE, root-mean-square error]

Well (fig. 2)	Model cell (row, column shown in fig. 13)	Mean difference	Standard deviation of difference	RMSE of difference
USGS–3	26,28	0.85	0.34	0.91
USGS–5	16,15	-.22	.48	.52
USGS–6	11,9	-.24	.43	.49
USGS–9	28,24	.41	.34	.53
USGS–12	36,28	.26	.32	.41
USGS–13	30,22	-.19	.39	.43

base flow were 2.45 and 0.58 ft^3/s, respectively. At the end of the simulation period, the cumulative daily mean total streamflow decrease for May 1993 caused by pumping was about 185 acre-ft, of which induced infiltration was 150 acre-ft or about 81 percent of the streamflow decrease, and intercepted base flow was 35 acre-ft or about 19 percent of the streamflow decrease (fig. 20*C*). Well-field pumpage for May was about 265 acre-ft; thus, about 57 percent was from induced infiltration from the river, about 13 percent was from intercepted base flow, and the remainder of the pumpage (30 percent) came from decreased aquifer storage, outflow from the aquifer, evapotranspiration, and increased recharge and inflow to the aquifer.

Figure 21 shows the simulated daily and monthly mean ground-water altitudes, computed from model-cell values within the Junction City well-field area, and drawdown caused by pumping (the difference between ground-water altitudes in pumping and non-pumping simulations). The monthly mean ground-water altitude was 1,054.5 ft without pumping and 1,052.8 ft with pumping (fig. 21*A*). The monthly mean drawdown caused by pumping was about 1.64 ft (fig. 21*B*).

Verification of Model to November 1994 Conditions

Because the set of parameter values used in the calibrated model were developed for May 1993 hydrologic stresses, it was desirable to verify the model under a different set of stresses to help establish greater confidence in the model. A typical verification process is to use aquifer parameters determined during model calibration to simulate the hydrologic conditions for a different time period. November 1994 was selected as the verification time period because climatic conditions were much drier and streamflow was very small as compared to the wet, relatively large streamflow conditions of May 1993.

For the verification, it was not necessary to adjust values of hydraulic conductivity, specific yield, streambed vertical hydraulic conductivity, and recharge (as a percentage of precipitation). Satisfactory results were achieved using the same properties and recharge as used in the calibration simulation.

Determination of Initial Hydraulic Heads

For the transient simulation of November 1994, initial hydraulic heads were specified for each model cell in a two-step process. First, a steady-state model simulation using the mean precipitation and streamflow conditions and mean pumping rates for October 1994 was used to specify a set of starting heads. Second, these heads were manually adjusted up or down in local areas to more closely match measured heads in observation wells and to minimize aquifer-storage changes at the beginning of transient simulations.

Table 7. Simulated water budget for alluvial aquifer for May 1993 model simulation and comparison of simulated and conceptual water-budget differences

[Values are in cubic feet per second. +, recharge is greater than discharge; -, recharge is less than discharge]

Budget term	Simulated recharge to aquifer	Simulated discharge from aquifer	Simulated water-budget difference between recharge and discharge	Conceptual water-budget difference between recharge and discharge (table 4)
Recharge from precipitation	13.80	0	+13.80	+14
Subsurface inflow (recharge) and outflow (discharge)	3.49	2.14	+1.35	+1.4
Seepage for Republican River	32.56	11.45	+21.11	+38.9
Seepage for Smoky Hill River	23.58	13.63	+9.95	+8.4
Well pumpage	0	8.91	-8.91	-8.91
Aquifer storage	37.37	74.57	-37.20	-54
Total	**110.80**	**110.70**	**+.10**	**-.21**

Comparison of Measured to Simulated Potentiometric Surfaces, River Water-Surface Altitudes, and Hydraulic Heads

Several comparisons were made during the verification process among the measured and simulated potentiometric surfaces (fig. 22), measured and simulated river water-surface altitudes (fig. 23), and the measured and simulated ground-water altitudes for selected observation wells (fig. 24). In the Junction City well field, positional differences between measurement-based and simulation-based potentiometric contours may be the result of time and area discretization in the ground-water flow model. In the model, pumping was simulated as a daily total value averaged over 24 hours and is evenly distributed over the area of a model cell, whereas, in reality, pumping may only have occurred for a few hours and at a point location within the model cell. This means that simulated drawdown was less than in reality because a smaller pumping rate was simulated and was spread out over a larger area. Also, differences may result from day-long simulation of pumping, whereas the pump may actually have been off when the water level was measured.

In general, the simulated river water-surface altitudes match well with the measured ones, with an RMSE of about 0.06 ft. Simulated daily mean ground-water altitudes match measured ground-water altitudes well in terms of shapes and altitudes. The maximum RMSE for ground-water altitudes in the selected observation wells was 0.53 ft (table 8).

Comparison of Simulated and Conceptual Water Budgets

A simulated water budget for the November 1994 model verification is listed in table 9. Both the Republican and Smoky Hill Rivers generally gained water from the aquifer. Other simulated and conceptual budget values are similar (table 9).

Simulated Streamflow Decrease Induced by Municipal Well Pumping

The model, using climatic conditions of November 1994 (fig. 16), was used to simulate the streamflow decrease in the Republican River induced by pumping of Junction City municipal wells and the consequential effects on ground-water levels. Two simulations were conducted, one with and one without pumping.

The Republican River gained an average of 2.27 ft^3/s during November 1994 without pumping; however, with pumping, the Republican River lost an average of 0.88 ft^3/s (fig. 25*A*). Monthly mean total streamflow decrease was 3.15 ft^3/s, the monthly mean induced infiltration was 1.0 ft^3/s, and the monthly mean intercepted base flow was 2.15 ft^3/s (fig. 25*B*). At the end of the simulation period, the cumulative daily mean total streamflow decrease for November 1994 caused by pumping was about 187 acre-ft, of which induced infiltration was about 59 acre-ft or about 32 percent of the total streamflow decrease and intercepted base flow was about 128 acre-ft or about 68 percent of the total streamflow decrease (fig. 25*C*). Well-field pumpage for November was about 264 acre-ft, of which about 22 percent was from induced

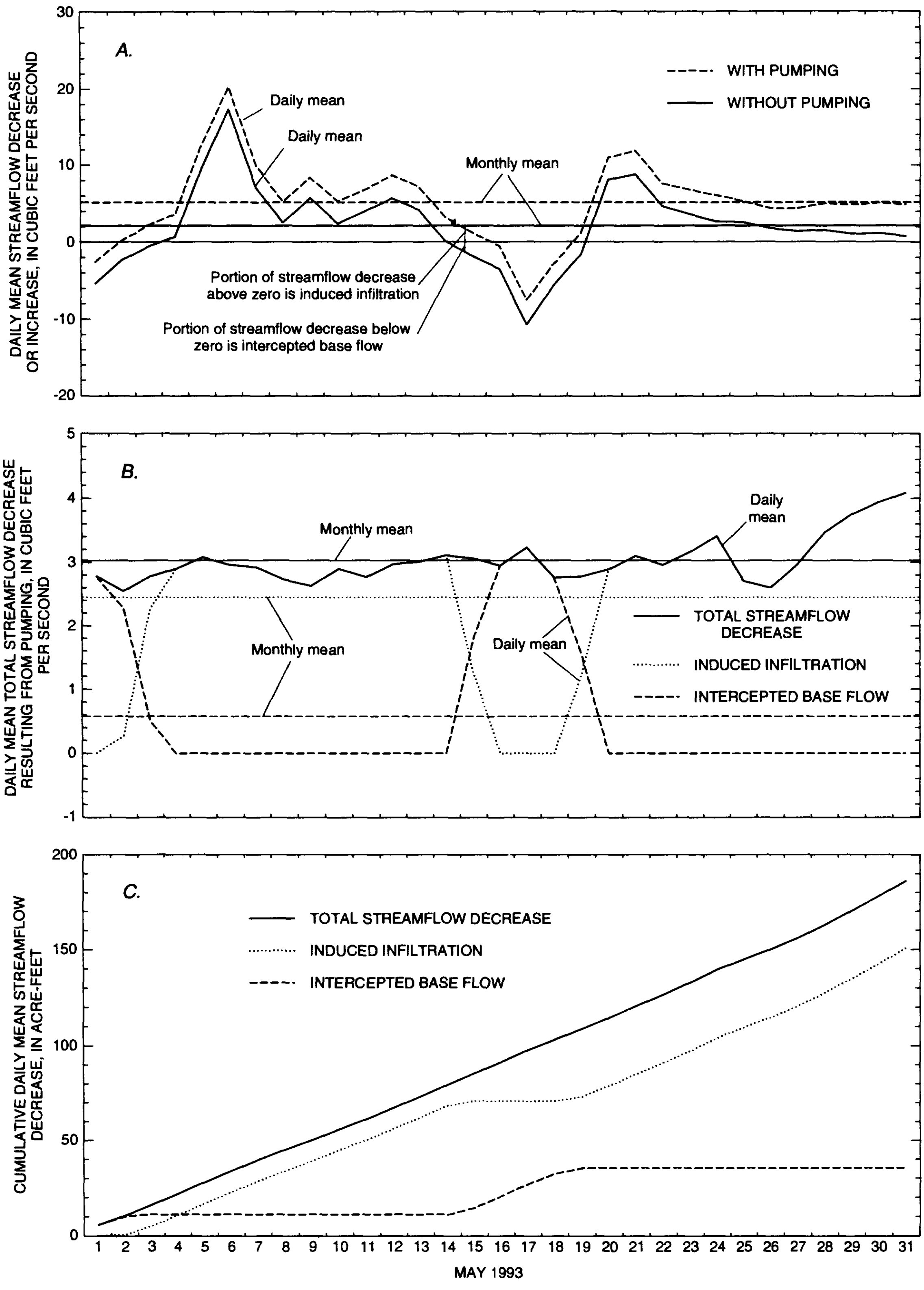


Figure 20. Simulated May 1993 (*A*) daily mean streamflow decrease from Republican River near Junction City municipal well field with and without pumping, (*B*) daily mean total streamflow decrease and stream and ground-water contributions to daily mean total streamflow decrease caused by pumping, and (*C*) cumulative daily mean total streamflow decrease and stream and ground-water contributions to cumulative daily mean total streamflow decrease caused by pumping.

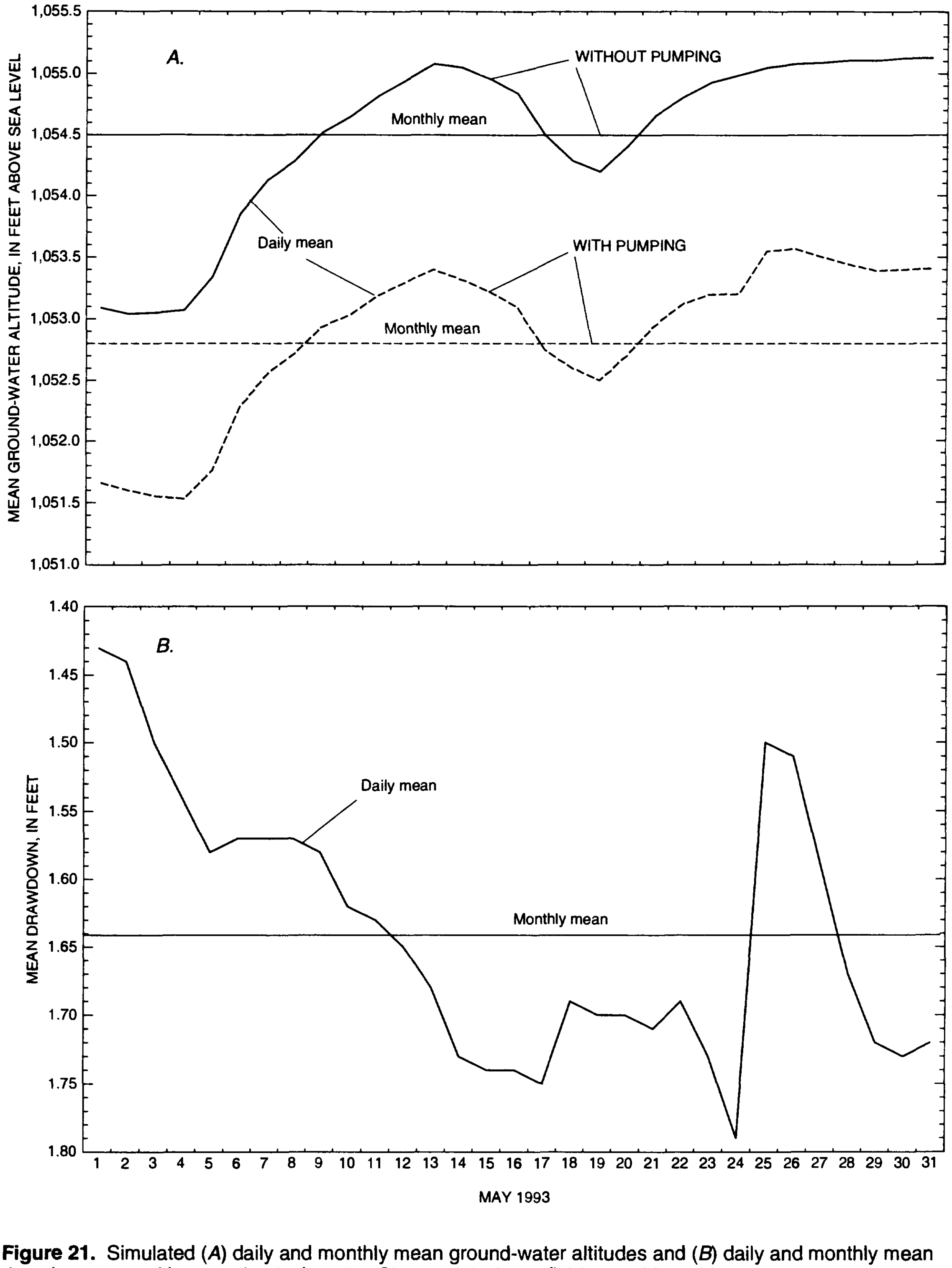
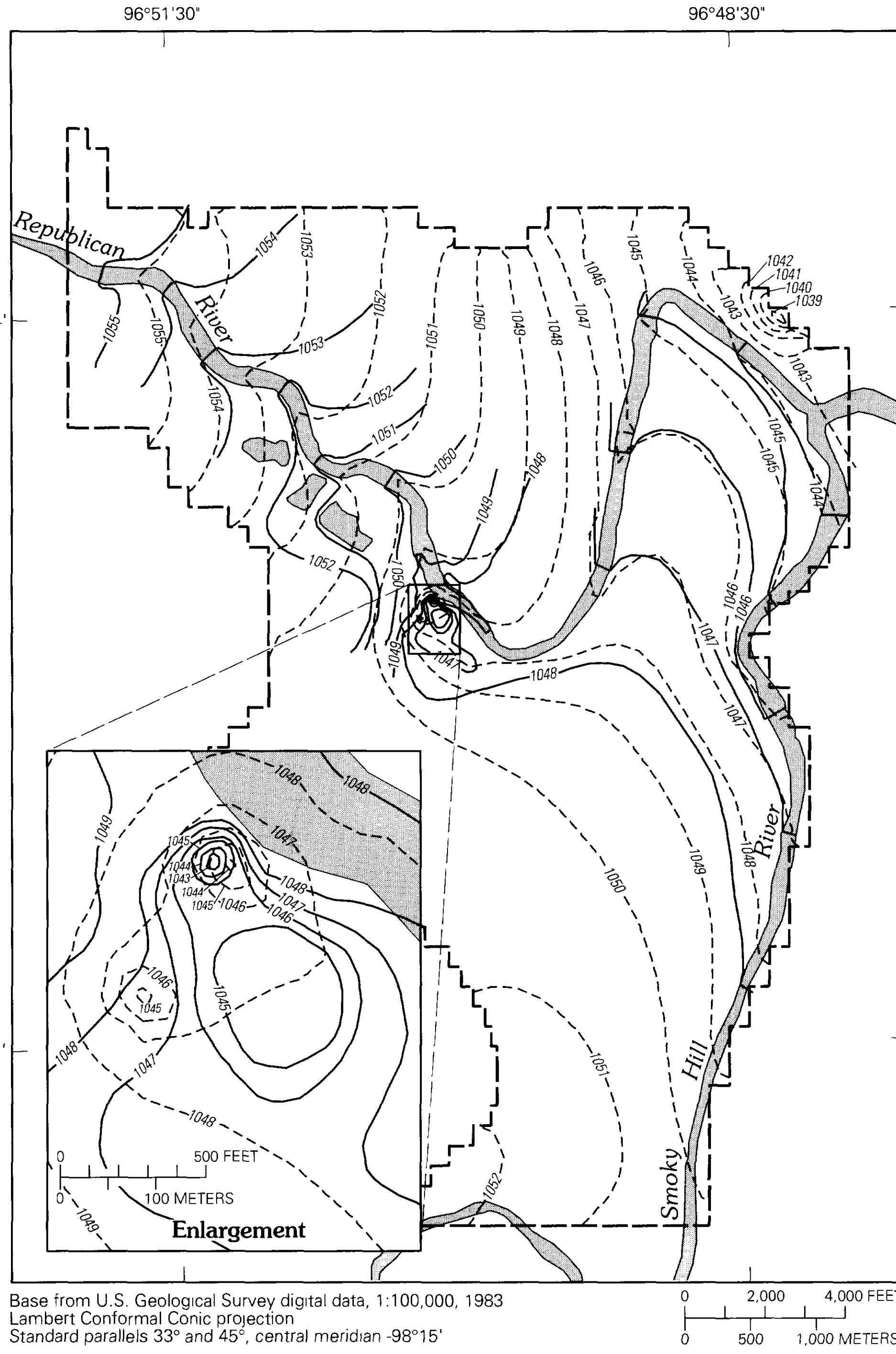


Figure 21. Simulated (*A*) daily and monthly mean ground-water altitudes and (*B*) daily and monthly mean drawdown caused by pumping in Junction City municipal well-field area, May 1993.



EXPLANATION

—1050— **Potentiometric contour from measured data**—Shows altitude at which water level would have stood in tightly cased wells. Contour interval 1 foot. Datum is sea level

- -1050- - **Potentiometric contour from simulation**—Shows simulated altitude at which water level would have stood in tightly cased wells. Contour interval 1 foot. Datum is sea level

— — — **Boundary of active modeled area**

Figure 22. Measurement-based and simulation-based potentiometric surfaces for November 8–9, 1994.

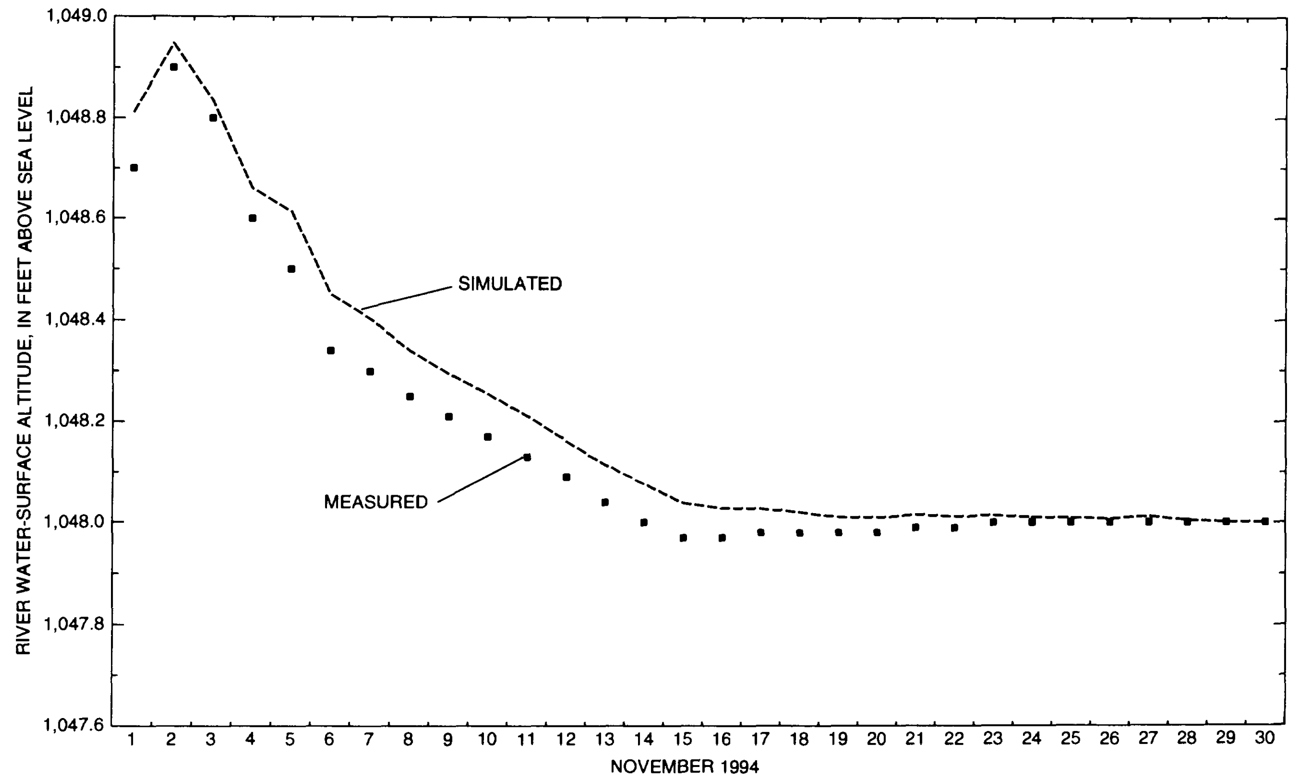


Figure 23. Measured and simulated daily mean river water-surface altitudes for Republican River at Junction City municipal well field, November 1–30, 1994.

infiltration from the river, about 48 percent was from intercepted base flow, and the remainder of the pumpage (30 percent) came from decreased aquifer storage, outflow from the aquifer, evapotranspiration, and increased recharge and inflow to the aquifer.

The daily and monthly mean ground-water altitudes in the Junction City municipal well field and the drawdown caused by pumping are shown in figure 26. Ground-water levels decreased more rapidly with pumping than without pumping. The monthly mean ground-water altitude was 1,049.4 ft without pumping and 1,047.9 ft with pumping (fig. 26*A*). The drawdown due to pumping was about 1.7 ft at the end of the simulation period (fig. 26*B*). The monthly mean drawdown caused by pumping was about 1.5 ft.

Simulations of Hypothetical Conditions

The simulative capabilities of the calibrated and verified model permit hydrologic response to be evaluated by changing data input to simulate various hypothetical conditions. A series of steady-state simulations was made to compare ground-water levels in the well-field area to various pumpage and streamflow options. Results of the steady-state simulations represent long-term (1 year or more) average pumping, recharge, streamflow, and hydraulic-head conditions. Steady-state simulations preclude changes in aquifer storage and thus may overestimate or underestimate streamflow decreases and hydraulic heads for shorter time periods. In the actual stream-aquifer system, precipitation, and thus recharge, streamflow, and storage vary daily, seasonally, and yearly, so that the stream-aquifer system is in a state of dynamic equilibrium and hydraulic heads and flow between the stream and aquifer vary in relation to long-term average values.

Hypothetical Conditions

Hypothetical conditions used for simulations were combinations of various precipitation, pumpage, and Republican River streamflow. Precipitation values were determined by taking percentages of the long-term mean annual precipitation of 32.88 in. observed at Manhattan (National Oceanic and Atmospheric

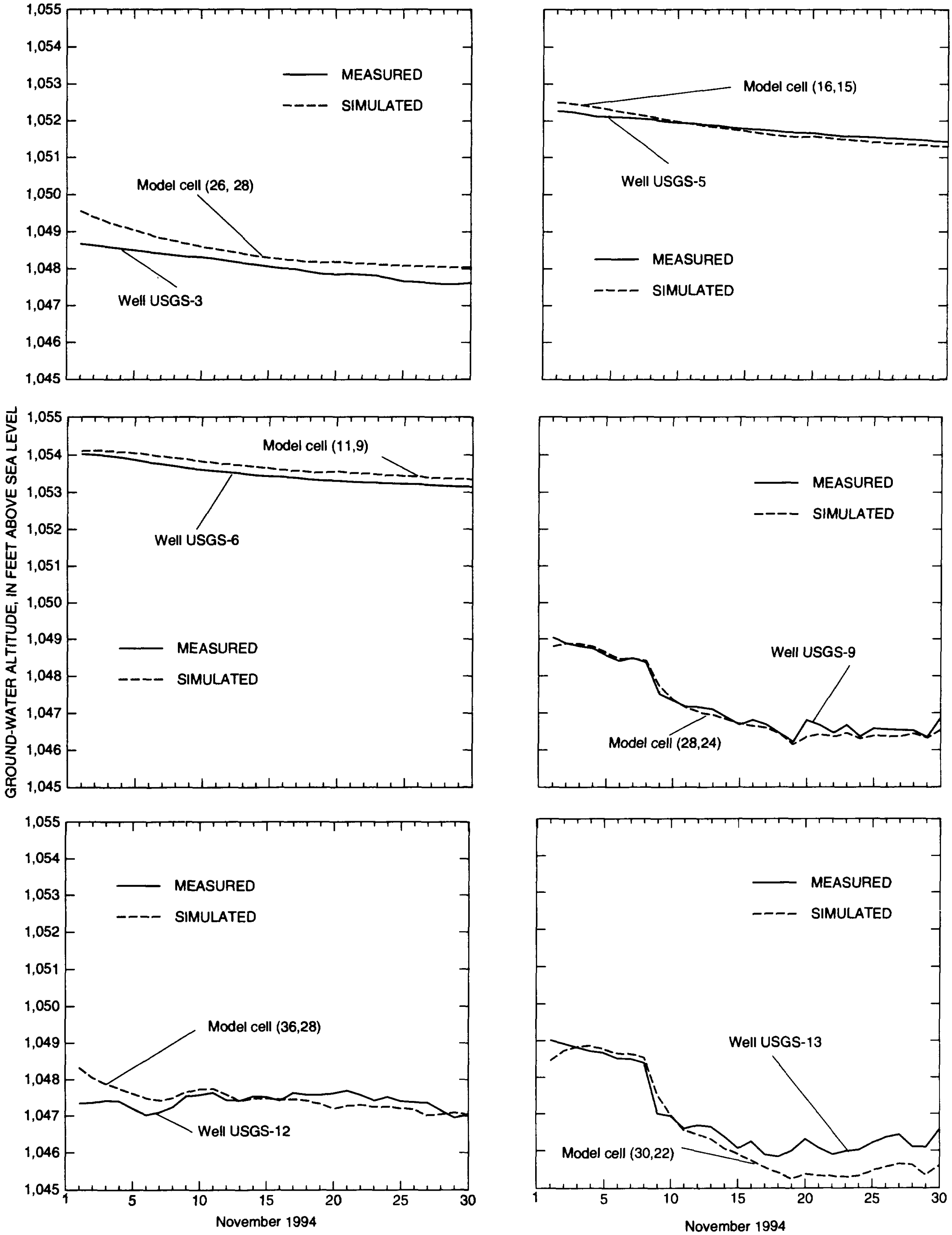


Figure 24. Measured and simulated daily mean ground-water altitudes for selected observation wells in model area, November 1–30, 1994.

Table 8. Difference between measured and simulated daily mean ground-water altitudes, November 1994

[Values are in feet. RMSE, root-mean-square error]

Well (fig. 2)	Model cell (row, column shown in fig. 13)	Mean difference	Standard deviation of difference	RMSE of difference
USGS–3	26,28	-0.40	0.16	0.43
USGS–5	16,15	.01	.13	.13
USGS–6	11,9	-.20	.04	.20
USGS–9	28,24	.08	.14	.16
USGS–12	36,28	-.05	.34	.33
USGS–13	30,22	.36	.39	.53

Administration, 1993–94). The percentages used were 0, 25, 50, and 100 percent, or 0, 8.22, 16.44, and 32.88 in., respectively. The percentage of precipitation that was recharged to the aquifer was assumed to be 15 percent, as used during model calibration.

Five pumpage rates were used in the simulations of hypothetical conditions: (1) no pumpage, (2) the 1993 mean pumpage, (3) the maximum allowable pumpage, (4) 1.5 times the maximum allowable pumpage, and (5) 2.0 times the maximum allowable pumpage. Because maximum allowable pumpage has not been established for Fort Riley supply wells, the mean pumpage for 1993 was used to represent maximum allowable pumpage for these wells. The 1993 mean pumpage used for Junction City municipal wells was 4.65 ft^3/s, and the maximum allowable pumpage used was 6.44 ft^3/s. The 1993 mean pumpage for Fort Riley supply wells was 4.97 ft^3/s. The maximum allowable pumpage used for agricultural and industrial wells was 0.40 ft^3/s. Hypothetical streamflows used in the simulations for the Republican River ranged from the Kansas minimum desirable streamflow of 25 (K.S.A. 82a.703) to 10,000 ft^3/s.

Results of Simulations

The various combinations of hypothetical stress conditions just discussed were used as the basis for 324 steady-state simulations. Figures 27–30 show the relations among simulated average and minimum ground-water-level altitudes in the Junction City well-field area (fig. 13) for various hypothetical precipitation rates, pumpages, and Republican River streamflows. These simulated average and minimum ground-water-level altitudes represent long-term average conditions where hydraulic head in the aquifer is in equilibrium with recharge, streamflow, and pumping stresses.

Because the distribution of pumping differed for the simulation using 1993 mean pumpage and the simulations using maximum allowable or multiples of maximum allowable pumpage, the minimum ground-water-level altitude in the well-field area occurred in two different locations. For 1993 mean pumpage, the miminum simulated ground-water level occurred in model cell row 33, column 22 (fig. 14), corresponding to municipal well CITY–16, and for maximum allowable or multiples of maximum allowable pumpage, the minimum simulated ground-water level occurred in model cell row 39, column 27, corresponding to municipal well CITY–8.

For any specified simulated precipitation rate, simulated pumpage rate, and a selected ground-water altitude, an associated streamflow can be determined. For example, figure 27 shows that given zero precipitation (and recharge), the 1993 mean pumpage rate, and a streamflow of 500 ft^3/s, the approximate average ground-water altitude in the well field would be 1,048.4 ft, and the approximate minimum ground-water level in the well field would be 1,046.4 ft. The ground-water altitudes would be 1,047.0 and 1,045.0 ft for the average and minimum, respectively, if the streamflow was 30 ft^3/s. Thus, for management purposes, the approximate streamflow required to maintain ground-water levels in the well field at a desirable altitude can be interpolated from these curves.

Figure 31 shows the relations among the simulated minimum ground-water-level altitudes in the well-field area and the ground-water-level altitudes for the model cell at row 31, column 20. The model cell at row 31, column 20, was selected for this comparison because observation well CITYOBS–17 is located in this cell and is measured periodically by city personnel. Observation well CITYOBS–17 also is farther from pumping wells than any of Junction City's other observation wells and, thus, should be the best indicator of average ground-water levels in the well-field area. Simulated ground-water levels in the model cell at row 31, column 20, are about 1.5 to 5.5 ft higher than the simulated minimum ground-water levels in the well-field area; larger pumping rates produce a

Table 9. Simulated water budget for alluvial aquifer for November 1994 model simulation and comparison of simulated and conceptual water-budget differences

[Values are in cubic feet per second. +, recharge is greater than discharge; -, recharge is less than discharge]

Budget term	Simulated recharge to aquifer	Simulated discharge from aquifer	Simulated water-budget difference between recharge and discharge	Conceptual water-budget difference between recharge and discharge (table 4)
Recharge from precipitation	2.24	0	+2.24	+2.2
Subsurface inflow (recharge) and outflow (discharge)	.80	.97	-.17	-.06
Seepage for Republican River	2.68	11.12	-8.44	-14.0
Seepage for Smoky Hill River	.08	6.24	-6.16	-4.2
Well pumpage	0	8.08	-8.08	-8.08
Aquifer storage	23.16	1.59	+21.57	+24
Total	**28.96**	**28.00**	**+.96**	**-.14**

larger difference between the minimum ground-water altitude and the ground-water level for the model cell at row 31, column 20. Simulated ground-water levels for the model cell at row 31, column 20, are from zero to 0.6 ft higher than the simulated average ground-water level in the well-field area.

Figures 27–31 also illustrate other aspects of the relations among simulated average water-level altitudes in the well-field area and various hypothetical precipitation rates, pumpages, and streamflows. Ground-water-level drawdown caused by pumping in the well field decreases as precipitation and streamflow increase. The mean drawdown in the well-field area for all 324 simulations, using 1993 mean pumpage, was about 2.1 ft and ranged from about 1.8 to 2.3 ft. This small range indicates that under steady-state conditions drawdown is not very sensitive to changes in precipitation or streamflow.

Ground-water levels in the well-field area rise as precipitation and streamflow increase. Simulated average ground-water levels rise by about 0.1 in. per inch of increased precipitation. The average ground-water level also rises as streamflow increases but is primarily controlled by stream stage, which is a function of streamflow and channel cross-sectional area, slope, and roughness.

For the steady-state simulations of hypothetical conditions, the magnitude of streamflow decrease (intercepted base flow plus induced infiltration—see fig. 11) in the Republican River for the Junction City well-field area generally is controlled by recharge from precipitation, streamflow, and well-field pumpage, provided that stream-channel geometry and streambed hydraulic properties remain unchanged. Changes in streamflow decrease in the well-field area for various precipitation rates are small (table 10). Similarly, changes in streamflow decrease are small (0.08 ft^3/s or less) for the range of streamflow from 25 to 10,000 ft^3/s. Changes in streamflow decrease are small in these cases because only the local well-field area was considered and because steady-state simulations assume that hydraulic head in the aquifer is in equilibrium with recharge, streamflow, and pumping stresses. A specified recharge rate or streamflow will produce higher or lower hydraulic heads in the aquifer but, compared to the effect of pumping Junction City municipal wells, will produce only small changes in the amount of water flowing between the stream and aquifer in the well-field area for the long term. Changes in pumping have a much larger effect on streamflow decrease in the well-field area than changes in recharge or streamflow (table 10). Under transient conditions, changes in recharge or streamflow may produce large but temporary changes in the amount of water flowing between the stream and aquifer, but these changes would diminish with time and eventually would approach the steady-state values if recharge and streamflow stabilize. The steady-state simulations approximate long-term average values.

The digital model is, by its nature, a simplification of the natural stream-aquifer system and can not reproduce the level of geologic or hydrologic detail present in the natural system. The digital model is limited in representing the natural stream-aquifer system by the

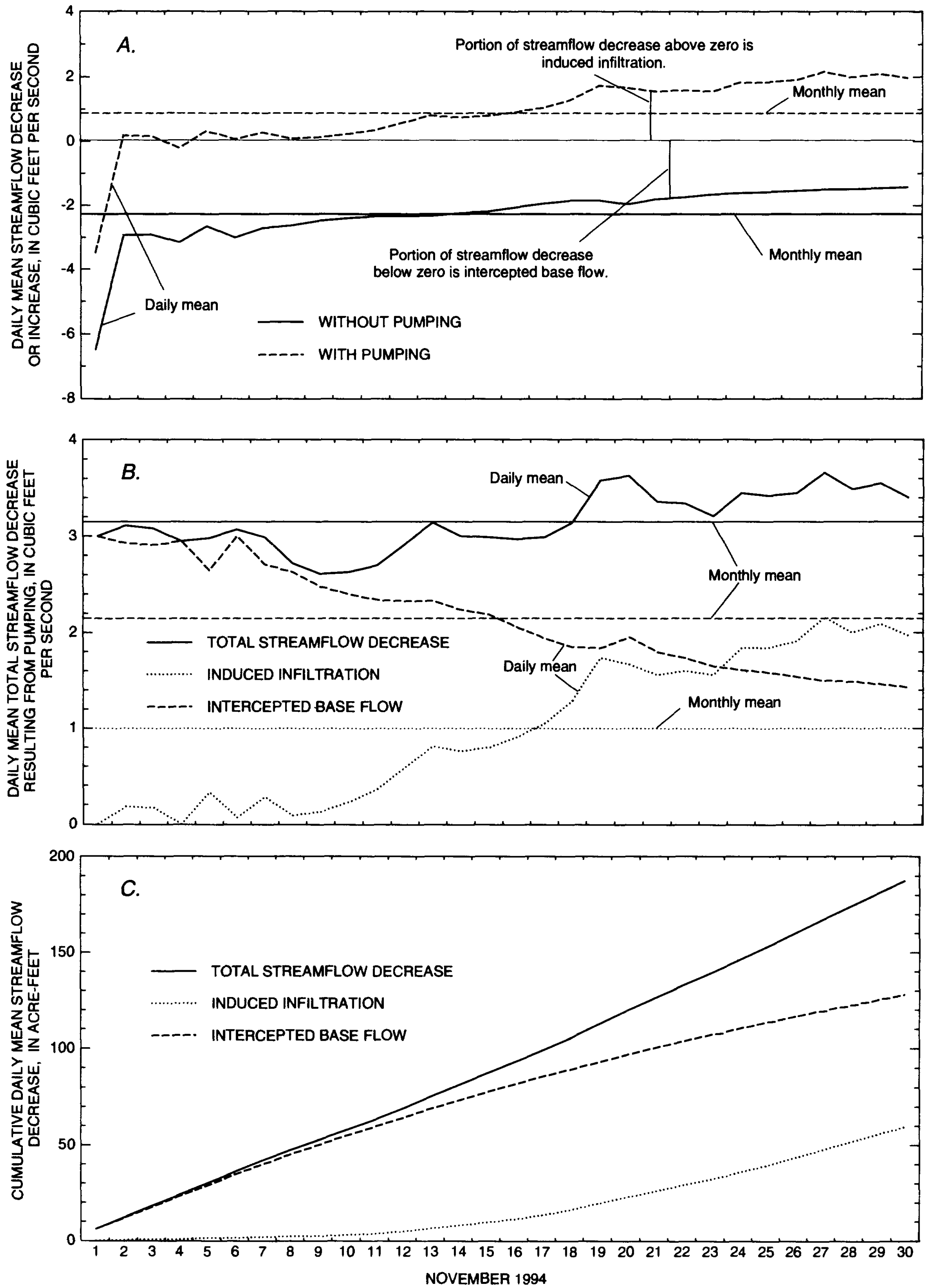


Figure 25. Simulated November 1994 (*A*) daily mean streamflow decrease from Republican River near Junction City municipal well field with and without pumping, (*B*) daily mean total streamflow decrease and stream and ground-water contributions to total streamflow decrease caused by pumping, and (*C*) cumulative daily mean total streamflow decrease and stream and ground-water contributions to cumulative daily mean total streamflow decrease caused by pumping.

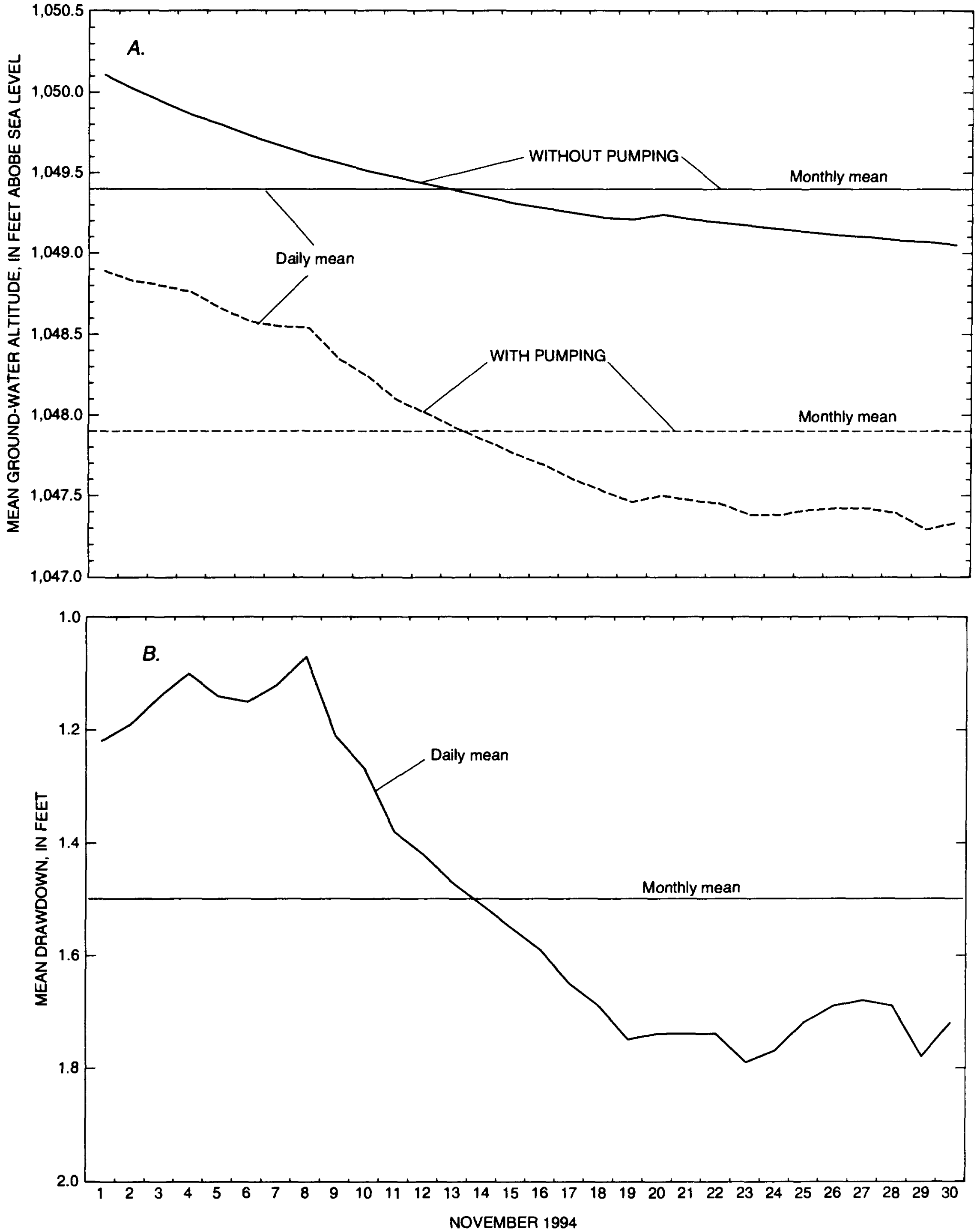


Figure 26. Simulated (*A*) daily and monthly mean ground-water altitudes and (*B*) daily and monthly mean drawdown caused by pumping in Junction City municipal well-field area, November 1994.

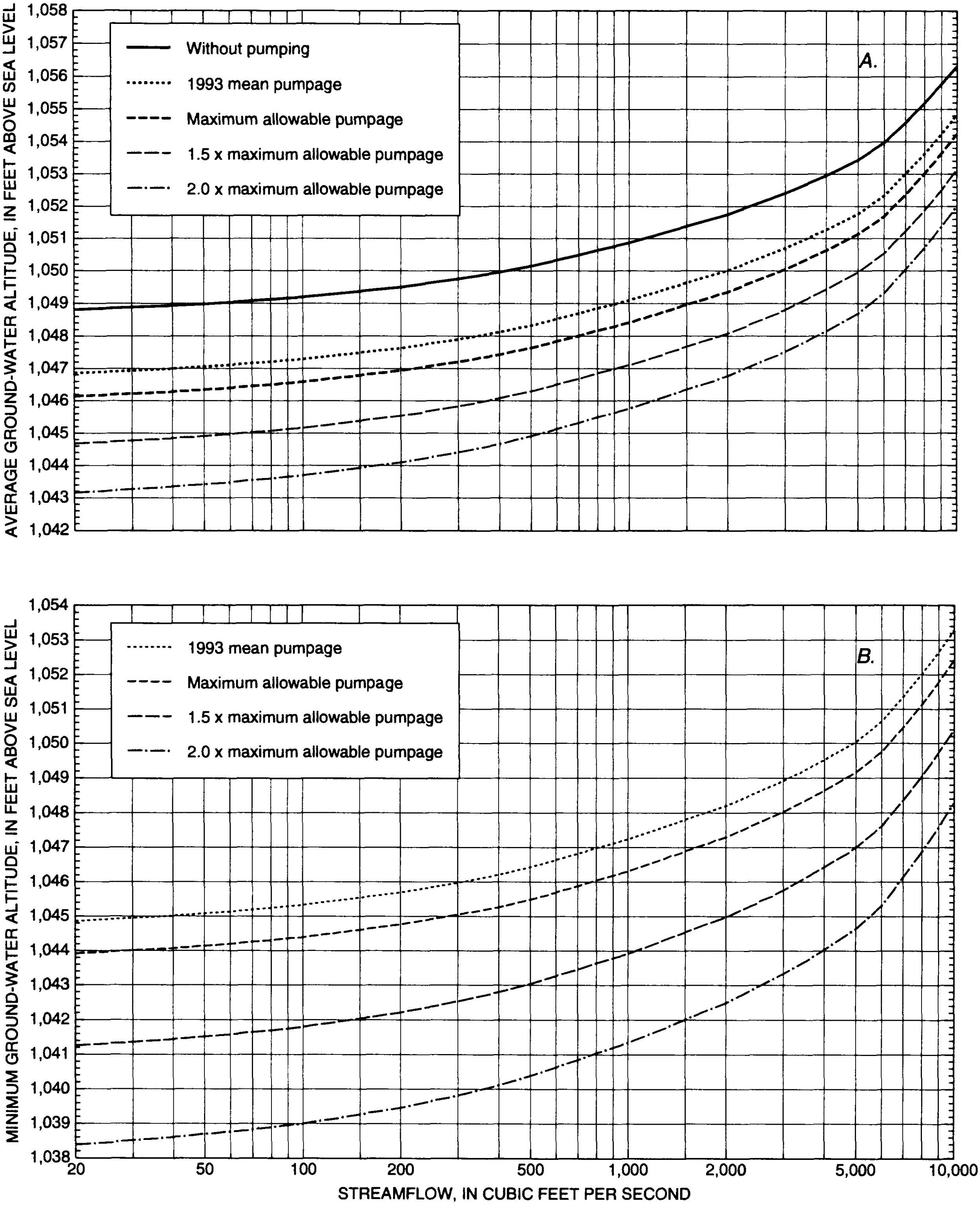


Figure 27. Relations among (*A*) average and (*B*) minimum simulated ground-water altitudes in Junction City municipal well-field area and streamflow in Republican River simulated with zero precipitation.

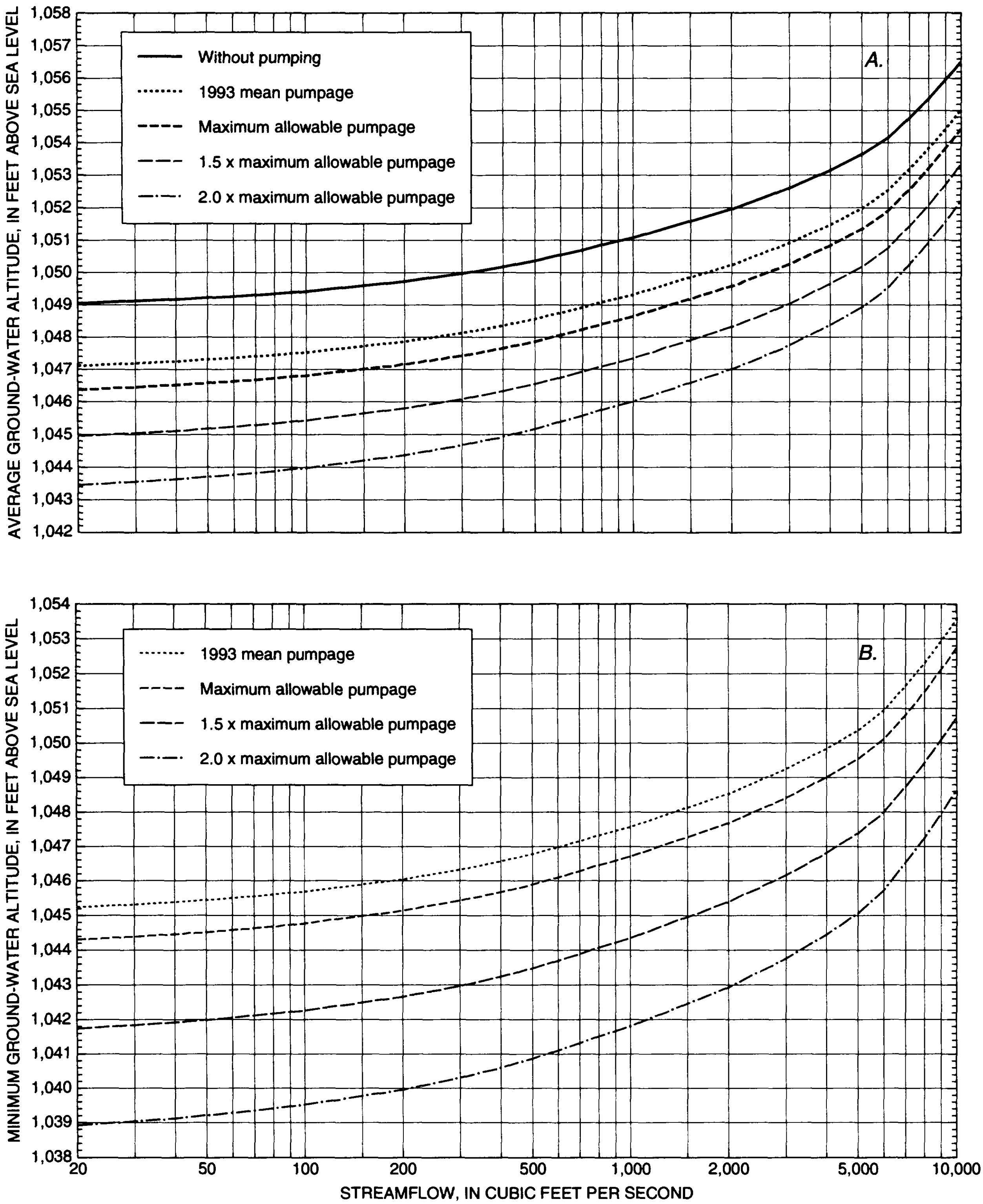


Figure 30. Relations among (*A*) average and (*B*) minimum simulated ground-water altitudes in Junction City municipal well-field area and streamflow in Republican River simulated with 32.88 inches of precipitation per year.

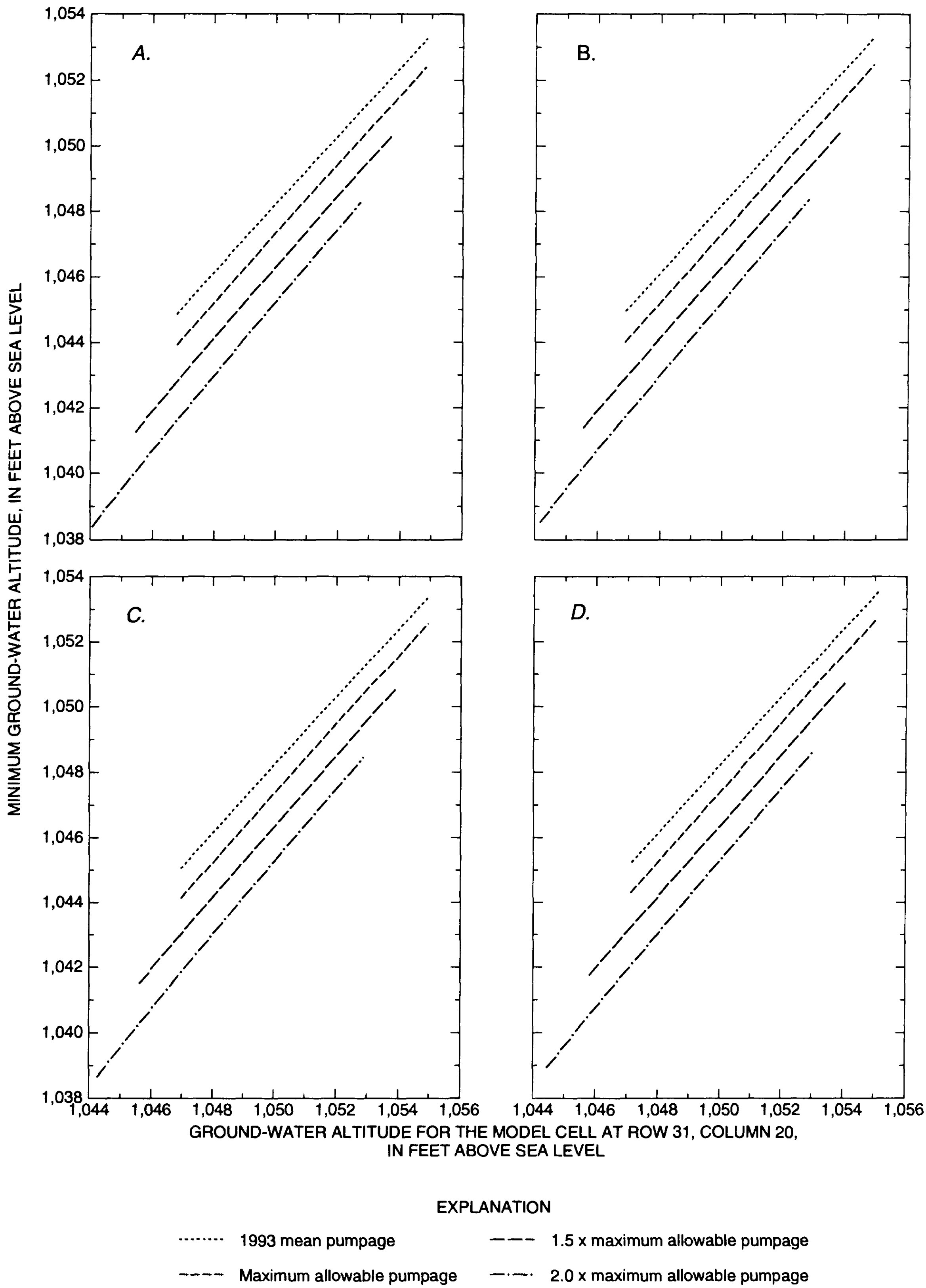


Figure 31. Relations among simulated ground-water altitudes at model cell row 31, column 20 (location of observation well CITYOBS–17), and simulated minimum ground-water altitudes in Junction City municipal well-field area simulated with (*A*) zero, (*B*) 8.22, (*C*) 16.44, and (*D*) 32.88 inches of precipitation per year.

Table 10. Steady-state streamflow decrease for simulations of hypothetical conditions

[Values are mean streamflow decreases for simulated streamflow discharges from 25 to 10,000 cubic feet per second]

Annual precipitation (inches)	Republican River steady-state streamflow decrease (cubic feet per second) for indicated Junction City municipal well pumpage				
	Without pumping	1993 mean pumpage	Maximum allowable pumpage	1.5 x maximum allowable pumpage	2.0 x maximum allowable pumpage
0	0.16	4.63	5.32	7.92	10.49
8.22	.04	4.51	5.20	7.80	10.38
16.44	[1]-.08	4.39	5.08	7.68	10.25
32.88	[1]-.31	4.15	4.85	7.44	10.02

[1]Negative streamflow decrease indicates gaining stream.

accuracy of measurements of hydraulic conductivity, aquifer thickness, recharge, streamflow, and pumping and by the spatial and temporal discretization of these parameters in the model. Because of these limitations, the digital model may not accurately represent hydrologic stresses such as the location of cones of drawdown caused by pumping wells or the duration of transient stresses such as well pumping, changing streamflow, or precipitation. None-the-less, the digital model is a useful tool for projecting the average or long-term effects of hydrologic stresses, such as municipal well-field pumping, on the hydrologic system.

SUMMARY AND CONCLUSIONS

Beginning in 1992, separate 3-year studies were undertaken to determine the effects of pumping municipal wells in the alluvial aquifer at Junction City and Manhattan, Kansas, on streamflows in the Republican, Big Blue, and Kansas Rivers. This report describes the effects of known and hypothetical municipal well-field pumping at Junction City on streamflow in the Republican River.

A network of observation wells, including wells drilled during the study, was established for the purpose of collecting water-level data in and around the well field. Ten of these wells were equipped with water-level recording instruments; other wells in the network were measured with a steel tape about monthly. A stage-only gaging station on the Republican River was established at the edge of the Junction City well field and was equipped with a water-level recording instrument. The vertical hydraulic conductivity of the Republican River streambed near the well field was determined by using a potentiomanometer and a seepage meter. Descriptions of geologic materials were recorded while drilling, and gamma-ray logs were obtained from wells drilled to bedrock during the study. Water levels were used to construct potentiometric-surface maps for selected dates. Seepage surveys of Republican River streamflow were conducted to help determine the effects of municipal well-field pumping on streamflow.

The study area is located in the alluvial and terrace deposits of the Republican, Smoky Hill, and Kansas Rivers. The alluvium consists of as much as an 80-ft thick sequence of gravel, coarse-to-fine sand, and silt, with interbedded clay layers and with the coarsest sediments generally near the bottom of the alluvial deposits. Terrace deposits consist of fining-upward sequences of gravel, sand, silt, and clay. Alluvial and terrace deposits are underlain by shale and limestone of Permian age.

Flow in the Republican and Smoky Hill Rivers, which join in the study area to form the Kansas River, and in the Kansas River was unregulated before the late 1950's and early 1960's when a series of dams was constructed for flood control and other purposes. Streamflow in the Republican River has been regulated by Milford Dam since August 1967. Outflow from Milford Reservoir generally is related to rainfall, but during periods of substantial precipitation or drought, releases are dictated by reservoir- and river-management needs. The Republican River channel downstream from Milford Dam has degraded in altitude because of sediment-starved conditions downstream from the dam. Streamflow in the Smoky Hill

River is regulated at Kanopolis Dam, about 180 river mi upstream from the study area.

Ground water in the alluvial aquifer and terrace deposits is unconfined throughout the study area. Saturated thickness ranges from zero to about 60 ft in the study area. Potentiometric-surface maps for May 1993 and November 1994 show that ground water in the alluvial aquifer generally flows down the valley in the direction of streamflow and either towards or away from the river, depending on the relative difference between stream stage and adjacent ground-water levels in the aquifer. When stream stage is lower, ground water flows toward the stream and the stream gains water, and when stream stage is higher, ground water flows away from the stream and the stream loses water. Water-level data collected during this study indicate that the Republican River and alluvial aquifer are an integrated system and that there is a strong correlation between river water-surface and ground-water altitudes. The degradation of the Republican River channel downstream from the reservoir and consequent decline in river stage of about 9 ft probably has caused a corresponding decline of ground-water levels and a decrease of saturated thickness in the alluvial aquifer. Hydraulic conductivities of the aquifer in the study area range from 230 to 1,030 ft/d as calculated from aquifer and specific-capacity tests. Specific yield at one location within the study area was calculated to be 0.20. Streambed vertical hydraulic conductivity for the Republican River ranged from 2 to 9 ft/d and was assumed to be 1 ft/d for the Smoky Hill River.

The effects of well pumping on streamflow depend on several factors including the hydraulic conductivity of the streambed and aquifer, the saturated thickness and specific storage or specific yield of the aquifer, the distance between the wells and river, and well-pumping rate. Pumping wells close to a stream affect streamflow sooner and to a greater extent than wells farther from the stream. Streamflow decrease because of well pumping may not consist entirely of water from the stream (induced infiltration) but may consist partially or entirely of ground water that would have discharged to the stream and become base flow in the stream under a nonpumping hydraulic gradient (intercepted base flow). Seepage surveys conducted in 1994 showed streamflow gains in the Republican River upstream from the well field and streamflow loss ranging from about 1 to 5 ft^3/s in the vicinity of the well field.

For a conceptual model of the stream-aquifer system, the alluvial aquifer was represented as an unconfined aquifer. Recharge to the aquifer may result from precipitation, subsurface inflow, seepage from streams, and agricultural and urban water applications. Discharge from the aquifer may result from pumping, seepage to streams, evapotranspiration, and subsurface outflow. Recharge from precipitation for May 1993 and November 1994 within the conceptual model area was estimated from precipitation data to be 14 and 2.2 ft^3/s, respectively. Subsurface inflow to the aquifer was estimated to be 3.3 and 0.75 ft^3/s for May 1993 and November 1994, respectively. Subsurface outflow from the aquifer was estimated to be 1.9 and 0.81 ft^3/s for May 1993 and November 1994, respectively. Seepage from streams during May 1994 was estimated to be 3.9 ft^3/s for the Republican River near the Junction City well field, 35 ft^3/s for the Republican River not near the well field, and 8.4 ft^3/s for the Smoky Hill River. Seepage from streams during November 1994 was estimated to be about 2.5 ft^3/s for the Republican River near the Junction City well field. Seepage to streams during November 1994 was estimated to be 16.5 ft^3/s for the Republican River not near the well field and 4.2 ft^3/s for the Smoky Hill River. Pumping-well discharges from the aquifer in the conceptual model area for May 1993 and November 1994 were 8.91 and 8.08 ft^3/s, respectively.

Steady-state and transient, finite-difference, ground-water flow simulations were used to represent the aquifer and the response of the stream-aquifer system. The one-layer, finite-difference, digital model grid consisted of 53 columns and 71 rows of variably sized cells, with the smallest cells located near the Junction City municipal well field. No-flow cells were used to represent the physical edge of the alluvial aquifer and an assumed ground-water flow divide under the Smoky Hill River. Constant-head cells were used to represent the hydraulic connection between the adjacent alluvial aquifer and the modeled part of the aquifer. River cells were used to represent the Smoky Hill River, and stream cells were used to represent the Republican River. Pumping cells were used to simulate pumpage out of the aquifer. Aquifer properties used in the calibrated digital model were: hydraulic conductivity, 650 ft/d north and 550 ft/d south of the Republican River; specific yield, 0.20; and streambed vertical hydraulic conductivities ranging from 1 to 5 ft/d. Stresses included in the model were recharge from precipitation, well pumpages, streamflow in the

Republican River, and stream stage in the Smoky Hill River.

The model was calibrated to May 1993 conditions and verified to November 1994 conditions. Calibration and verification involved a number of trial simulations in which values of hydraulic properties were adjusted within acceptable ranges. Initial hydraulic heads for the May and November transient simulations were determined using steady-state model simulations of climatic, pumping, and streamflow conditions occurring during the months preceding May or November.

For the calibration period, the maximum root mean square of the difference between measured and simulated ground-water altitudes at selected observation wells was 0.91 ft. Simulations of May 1993 conditions indicate that well-field withdrawals decreased simulated monthly mean streamflow by 3.03 ft^3/s for the month, of which 2.45 ft^3/s was contributed from the river (induced infiltration) and 0.58 ft^3/s was contributed from ground water that would have seeped to the river if the wells had not been pumping (intercepted base flow). At the end of the simulation period, about 57 percent of the total well-field pumpage (265 acre-ft) was induced infiltration from the river, about 13 percent was intercepted base flow, and the remainder (30 percent) was from decreased aquifer storage, outflow from the aquifer, evapotranspiration, and increased recharge and inflow to the aquifer.

For the November 1994 verification period, the maximum root mean square of the difference between measured and simulated ground-water altitudes at observation wells was 0.53 ft. Simulations of November 1994 conditions indicate that well-field withdrawals decreased simulated monthly mean streamflow by 3.15 ft^3/s for the month, of which 1.0 ft^3/s was induced infiltration and 2.15 ft^3/s was intercepted base flow. At the end of the simulation period, about 22 percent of the total well-field pumpage (264 acre-ft) was induced infiltration, about 48 percent was intercepted base flow, and the remainder (30 percent) was decreased aquifer storage, outflow from the aquifer, evapotranspiration, and increased recharge and inflow to the aquifer.

A series of 324 steady-state simulations of hypothetical conditions was made to compare ground-water levels in the Junction City well-field area to various precipitation, pumpage, and streamflow combinations. Pumping rates used in these simulations were (1) no pumping, (2) the 1993 mean pumpage, (3) the maximum allowable pumpage, (4) 1.5 times the maximum allowable pumpage, and (5) 2.0 times the maximum allowable pumpage. Hypothetical streamflows used in the simulations ranged from the Kansas minimum desirable streamflow of 25 to 10,000 ft^3/s, and recharge was 15 percent of precipitation (which ranged from zero to 32.88 in/yr). The steady-state simulations approximate long-term average hydraulic head and flow between the stream and aquifer.

On the basis of the simulations, the streamflow required to produce a desired average ground-water altitude in the well-field area was determined. For example, given no precipitation and the 1993 mean pumpage rate, a streamflow of 500 ft^3/s is required to produce an average ground-water-level altitude in the well-field area of 1,048.4 ft. The mean drawdown in the well-field area for all 324 simulations was about 2.1 ft and is not very sensitive to changes in precipitation or streamflow. For the steady-state simulations, the effect of changes in precipitation or streamflow on streamflow decrease was small compared to the effect of pumping on streamflow decrease.

The digital model is a simplification of the stream-aquifer system and is limited in simulating the natural system by the accuracy of data used to construct the model and by spatial and temporal discretization. None-the-less, the digital model is a useful tool for projecting the long-term effects of hydrologic stresses on the hydrologic system.

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SUPPLEMENTAL INFORMATION

Table 11. Lithologic logs of wells drilled by U.S. Geological Survey and Kansas Water Office during this study

[All altitudes are referenced to sea level and are reported to the nearest 0.01 foot. Depth to bottom of interval is reported in feet below land surface. Location of wells shown in figure 2]

Observation well USGS–1—Drilled November 10, 1992.
Altitude of land surface, 1,064.81 feet

	Thickness, in feet	Depth to bottom of interval, in feet
Silt, tan, fine; sand, tan, some soil present	6	6
Sand, tan, fine, becoming coarser near bottom of interval	14	20
Sand, tan-gray, medium-to-coarse, mostly quartz and feldspar with some limestone and chert; firm gravel layer at 36 to 38 feet, possible cobbles and boulders at bedrock contact; drilling stopped on hard bedrock	32	52

Observation well USGS–2—Drilled November 12, 1992.
Altitude of land surface, 1,064.98 feet.

	Thickness, in feet	Depth to bottom of interval , in feet
Silt, tan, fine; sand, tan, some soil present	6	6
Sand, tan, fine, grading coarser near bottom of the interval	14	20
Sand, tan-gray, medium-to-coarse, mostly quartz and feldspar with some limestone and chert gravel; drilling stopped in sand and gravel	8	28

Observation well USGS–3—Drilled November 13, 1993.
Altitude of land surface, 1,072.79 feet.

	Thickness, in feet	Depth to bottom of interval, in feet
Silt, tan, fine; sand, tan	4	4
Sand, tan, fine	21	25
Sand, orange, fine-to-medium, arkosic and quartzose with chert gravel	8	33
Sand, orange, fine-to-medium; some coarse sand, arkosic, quartzose, chert gravels	24	57
Gravel and cobbles, gray, composed of chert; drilling stopped on hard bedrock	4	61

Table 11. Lithologic logs of wells drilled by U.S. Geological Survey and Kansas Water Office during this study—Continued

Observation well USGS–4—Drilled November 13, 1992.
Altitude of land surface, 1,055.32 feet.

	Thickness, in feet	Depth to bottom of interval, in feet
Sand, orange, fine-to-medium, with some coarse, arkosic, quartzose, some chert and limestone gravel; drilling stopped in sand and gravel	10.5	10.5

Observation well USGS–5—Drilled November 16, 1992.
Altitude of land surface, 1,070.20 feet.

	Thickness, in feet	Depth to bottom of interval, in feet
Soil, brown	2	2
Silt, dark-tan to brown, clayey	1	3
Sand, light-tan, fine	16	19
Sand, fine-to-medium, with some coarse, arkosic, quartzose, pieces of limestone and flint; coarser material below 35 feet	22	41
Shale, gray, bedrock; drilling stopped	1	42

Observation well USGS–6—Drilled November 17, 1992.
Altitude of land surface, 1,076.93 feet.

	Thickness, in feet	Depth to bottom of interval, in feet
Soil, brown, silty	1	1
Sand, tan, fine	8	9
Clay, brown, silty to sandy	5	14
Sand, light-tan, fine	6	20
Sand, fine-to-medium, with some coarse arkose, quartzose, pieces of chert, and light-gray limestone gravels	18	38
Sand and gravel, tan-gray, coarse, arkosic, quartzose, some limestone and chert gravels; drilling stopped on shale bedrock	9.5	47.5

Table 11. Lithologic logs of wells drilled by U.S. Geological Survey and Kansas Water Office during this study—Continued

Observation well USGS–7—Drilled September 2 and 3, 1992.
Altitude of land surface, 1,082.35 feet.

	Thickness, in feet	Depth to bottom of interval, in feet
Soil, dark-brown, silty	3	3
Clay, tan, silty, firm	14	17
Sand, tan, silty	7	24
Clay, tan, silty-sandy	2	26
Sand and gravel, tan-orange, fining upwards, mostly quartz with feldspar, limestone, chert; coarse gravel at 50 and 59 feet and at bedrock contact, clay bed at 33 feet; drilling stopped on hard bedrock	45	71

Observation well USGS–8—Drilled November 17, 1992.
Altitude of land surface, 1,069.10 feet.

	Thickness, in feet	Depth to bottom of interval, in feet
Soil, dark-brown, silty	3	3
Silt, light-tan, slightly clayey	4	7
Sand, light-tan, fine, clean	7	14
Sand, tan-orange, fine-to-coarse, mostly quartz, with feldspar, limestone, and chert; grades coarser at 25 feet, coarse gravel at bedrock contact; drilling stopped on hard bedrock	43	57

Observation well USGS–9—Drilled January 27, 1993.
Altitude of land surface, 1,069.99 feet.

	Thickness, in feet	Depth to bottom of interval, in feet
Soil, dark-brown, silty	3	3
Silt, light-tan, slightly clayey	4	7
Sand, light-tan, clean	7	14
Sand, tan-orange, fine-to-coarse, mostly quartz, with feldspar, limestone, and chert; grades coarser at 25 feet; drilling stopped in sand and gravel	24	38

Table 11. Lithologic logs of wells drilled by U.S. Geological Survey and Kansas Water Office during this study—Continued

Observation well USGS–10—Drilled November 17, 1992.
Altitude of land surface, 1,054.58 feet.

	Thickness, in feet	Depth to bottom of interval, in feet
Sand, fine; drilling stopped in fine sand	6	6

Observation well USGS–11—Drilled November 17, 1992.
Altitude of land surface, 1,053.75 feet.

	Thickness, in feet	Depth to bottom of interval, in feet
Sand, fine; drilling stopped in fine sand	7	7

Observation well USGS–12—Drilled January 27, 1993.
Altitude of land surface, 1,067.41 feet.

	Thickness, in feet	Depth to bottom of interval, in feet
Soil, brown, clayey	2	2
Silt, tan, clayey	5	7
Sand, tan-orange, fine	5	12
Sand, tan, clayey	3	15
Sand, orange, medium-to-coarse, mostly quartz, some feldspar, limestone, chert; no clay zones present; coarser sand and gravel at 30 feet and at bedrock contact; drilling stopped on hard bedrock	41	56

Observation well USGS–13—Drilled January 28, 1993.
Altitude of land surface, 1,068.98 feet.

	Thickness, in feet	Depth to bottom of interval, in feet
Soil and clay, brown, silty	15	15
Silt, gray, clayey	15	30
Sand, medium-to-coarse, mostly quartz, some feldspar, limestone, chert; gravel at 45 feet; coarse near bedrock contact; drilling stopped on hard bedrock	28	58

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